**THE EFFECT OF URBANIZATION ON THE STREAMFLOWS OF THE SIMS BAYOU WATERSHED**

A Thesis

by

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Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

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May 2015

Major Subject: Civil Engineering

## ABSTRACT

The population growth in Houston over the last 30 years has been one of the fastest in the nation. Several studies have linked urbanization with increased runoff volume and peak discharges. For the watershed of Sims Bayou in the city of Houston, which has flat slopes, low permeability soils, and an aged storm water system, an increase in stream flows can signify an increase in flooding risk for a large number of people. Although attempts at solutions have been made by the USACE and HCFCD, increasing development in the area may be hindering those efforts.

This research study analyzes the flows and urbanization in the watershed through time to detect any trends. Annual peak flows and average daily flow records for two gages within the Sims Bayou watershed were analyzed and normalized by precipitation depths to diminish the variability of the time series caused by precipitation changes. Yearly development maps were developed using GIS. A yearly percent watershed developed value was then used to compare with the trends in flow. Since a positive relationship was observed between flows and urbanization for the selected gages, HEC-HMS was used to simulate the effect of urbanization alone on the watershed. By altering development values to reflect a development percentage similar to that occurring in the watershed in 1980, 1990, and 2000, the amount of runoff from the watershed for a 1% exceedance probability storm for development levels of 1980 and 2000 were compared. Changing development levels from 1980 to 2000 produced a 5% change in discharge at the watershed outlet. Using the results from HEC-HMS, a HEC-RAS model was used to

assess the impact of such changes on flooding risk for residents of the Sims Bayou watershed. Regulatory floodplains for development levels similar to those in the watershed for 1980, 1990, and 2000 were mapped and compared. The increase in floodplain area resulting from changing development levels was approximately 15%. Unless both low-impact development alternatives and policies are implemented, more development in the watershed could signify more flood losses in the future.

# DEDICATION

This Thesis is dedicated to my loving and supportive family.

## ACKNOWLEDGEMENTS

I would like to thank God for giving me a wonderful family to love, good opportunities to learn and grow, great teachers to help me navigate new lessons, and good friends to cheer me up.

I would like to thank my father, mother, brother, sister, and grandmother for being my support and my strength through all times. Without their lessons, patience, support, advice, encouragement, and love, I would not have achieved anything. I also want to thank my committee chair, Dr. Francisco Olivera, and my committee members, Dr. Philip Berke, and Dr. Anthony Cahill for their support, patience, understanding, and guidance during this research. I have learned greatly from them and am grateful to have had them on my committee. They are not only great professors, but great persons. I also want to thank my friends for being with me through tough times, encouraging me, and not allowing distance or time to separate us. I would also like to thank the Civil Engineering Department for making my years at Texas A&M University both challenging and rewarding and for having amazing faculty and graduate advising staff.

I also extend my gratitude to the Resilience and Climate Change Cooperative Project team for providing great insight into the needs of the Houston community and helping to shape this research. Finally, thanks to the Harris County Flood Control District and the Harris County Appraisal District and Fort Bend Central Appraisal Districts for providing assistance with hydrologic and hydraulic models and parcel data respectively.

## NOMENCLATURE

| | |
|---|---|
| DEM | Digital Elevation Model |
| FBCAD | Fort Bend Central Appraisal District |
| FEMA | Federal Emergency Management Agency |
| FIRM | Flood Insurance Rate Map |
| HCAD | Harris County Appraisal District |
| HCFCD | Harris County Flood Control District |
| HEC-HMS | Hydrologic Engineering Center- Hydrologic Modeling System |
| HEC-RAS | Hydrologic Engineering Center- River Analysis System |
| NOAA | National Oceanic and Atmospheric Administration |
| NFIP | National Flood Insurance program |
| NWIS | National Water Information System |
| NWS | National Weather Service |
| NRCS | Natural Resource Conservation Service |
| TIN | Triangular Irregular Network |
| USACE | United States Army Corps of Engineers |
| USGS | United States Geological Survey |

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# 1. INTRODUCTION

The state of Texas has experienced a rise in population that is above the national average according to the U.S. Census Bureau. The population of Texas ranks the 2nd highest nationally, and since 1980 the population density has increased from 65 people/sq. mi to over 93 people/sq. mi.(USCB 2012). The city of Houston tops the list of fastest growing cities in the state. In the past 30 years, Houston has grown from approximately 1.5 million people to almost 2.1 million equating to a 31.6% increase in the city's population. This large increase is not only felt in the City of Houston itself, but also in the surrounding suburbs as the city expands. This population growth is inevitably accompanied by an increase in land development and public infrastructure construction to accommodate the increasing number of people.

There has been a well-established relationship between changing flow regimes and urbanization. Through the increase of impervious cover in a watershed, urbanizations can alter the hydrologic behavior of the watershed. An increase past the 10% impervious cover threshold has been associated with increases in the maximum instantaneous stream flow (Beighley and Moglen 2002, Olivera and DeFee 2007). Additionally, stream and wetland degradation start to occur at the same 10% impervious cover threshold (Arnold 1996). At 30% impervious cover, 100 year flood volumes can double in comparison to the discharge of an undeveloped watershed (Hollis 1975). These findings show that not only do peak flows increase but more peaks occur as a result from runoff which was not generated in pre-development conditions. The creation of new peaks results in an increase in the frequency of any given discharge. In Flett Creek, for example, a discharge with a 10% probability of exceedance before development became a discharge with 67% exceedance probability after development (Moscrip and Montgomery 1997). Additionally, higher flows are associated with channel expansion, higher erosion rates, sediment deposition in low elevation areas, increased pollutant delivery to streams, and ecological disruptions (Booth 1991, Arnold 1996). However, urbanization does not affect the flow regime only by increasing runoff volumes during high precipitation events. It also has the effect of decreasing the stream flows during dry periods. This may be attributed to increased evapotranspiration and reduced groundwater recharge reducing the baseflow of the stream (Ferguson and Suckling 1990, Brun and Band 2000).Thus, urbanization results in not only a higher probability of flood events, but also a higher probability of low flow conditions.

The use of Geographic Information Systems (GIS) to analyze the spatial and temporal changes in watershed conditions has been very useful in improving accuracy and reducing model simplifications (Goonetilleke and Jenkins 1999). Census data, LandScan, and land use/land cover data have been used with GIS to estimate urbanization changes. Because of the correlation between population density and impervious cover, changes in population density has also been used as an indicator for urbanization (Arnold 1996, Sheng and Wilson 2009). Building permits, census data, and aerial photos were used by Leith and Whitfield (2000) to estimate when the biggest changes in urbanization occurred for their watershed of interest. For the period of 1968 to 1984, two subperiods were selected to represent pre-development and postdevelopment conditions and the discharges were analyzed. (Leith and Whitfield 2000). A similar approach was used by Moscrip and Montgomery (1997). In these studies, the difference in flow characteristics between the two periods was attributed to the differences in developed and undeveloped areas during the period of analysis (Moscrip and Montgomery 1997). However, these studies assume two static development stages and do not account for the spatial and temporal changes in development.

Using a GIS allowed studies such as Beighley and Moglen (2002), to study the urbanization in a watershed both at specified dates as well as a series through time using land use maps and aerial images to sort developed and undeveloped areas. In their series of studies, Beighley and Moglen introduced the use of geo-referenced property tax information in order to estimate impervious cover extending as far back as the late 1890s. Along with the use of aerial images and land use data, Beighly was able to analyze longer periods of time that could reflect substantial changes in urbanization (Beighley and Moglen 2002, Beighley and Moglen 2003). Olivera and DefFee (2007) used a similar approach by using geo-referenced parcel data to sort urbanization through time from 1949 to 2000. By analyzing the decade averaged flows, developing yearly development maps, and calculating yearly spatial metrics, they found that for a highly developed White Oak Bayou watershed, both precipitation and urbanization were responsible for changes in runoff and annual peak flows (Olivera and DeFee 2007).

While the link between traditional urbanization practices and changing flow regimes is well-documented, the management practices and strategies to handle urbanization vary. In Brunswick, Maine, for example, the watershed for Maquoit Bay must be kept to a maximum 5% impervious coverage, and in San Antonio, TX, city ordinances restrict the amount of impervious coverage. In both of these cases, the main concern of the community was the quality of their water resources (Arnold 1996). On the other hand, in Houston, TX, urbanization is welcomed and there is no limit on impervious coverage for new development or redevelopment. Yet, Houston has a history of severe flooding due to its extensive network of bayous, coastal proximity, and clayey soils.

## 2. PROBLEM DESCRIPTION

For Houston, the increase in urbanization coupled with the shallow coastal elevations can make flooding more frequent and severe. During Tropical Storm Allison in June 2001, Houston experienced major flooding throughout the city. Tropical Storm Allison dropped as much rainfall as to meet or exceed the 1%, 24-hr rainfall event in many areas of Houston. During its second pass through Harris County, as much as 28 inches of rain were measured in a 12 hour span. Total damages in the Houston area during Tropical Storm Allison totaled over five billion dollars and left 73,000 homes flooded (HCFCD 2010). For many of the older communities in the Houston area, it does not take a tropical storm Allison to find significant ponding occurring. Although Allison was particularly devastating to neighborhoods like Meredith Manor along Sims Bayou (Figure 1), communities such as Sunny Side and Manchester also located on the Sims Bayou watershed have an aged and low-capacity drainage system. The location of Manchester, for example, (at the convergence of Sims and Buffalo Bayous) coupled with inadequate drainage structures make any increase in stream flows a palpable problem.

Figure 1- Flooding in Sims Bayou caused by Tropical Storm Allison. (a) Homes flooded at Buffalo Speedway at Simsbrook, and (b) street flooding along Buffalo Speedway between West Orem and Fuqua

Growth in the City of Houston in the past 30 years may also be adding to the local flooding problems. The increase in urbanization not only translates to higher peak flows in the streams but also to a greater runoff volume that must be handled by the low-capacity drainage system (Moran 2010). The Harris County Flood Control District (HCFCD) and the City of Houston, along with organizations like Rebuild Houston, have attempted to improve the situation. Cooperation by the U.S. Army Corps of Engineers (USACE) and the HCFCD in projects like the widening and deepening of Sims Bayou, aim at reducing resident's flood risk. The Sims Bayou Federal Flood Damage Reduction Project, which was completed in late 2014, improved over 19 miles of streams and an estimated 35,000 homes were removed from the regulatory floodplain (Figure 2). A number of structural solutions such as channel improvements, bridge reconstruction, and the construction of regional water detention facilities promise to alleviate some of the risk, but with time, increasing development in the watershed may diminish the success of these structural improvements (HCFCD 2010, Moran 2010).

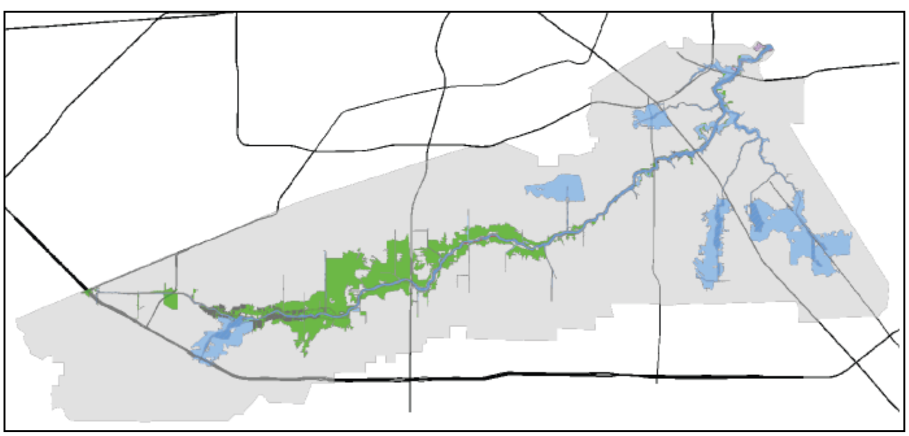


Figure 2- Change in regulatory floodplains along Sims Bayou due to the Federal Flood Reduction Project. Green areas in the map signify removal from regulatory floodplain.

# 3. STUDY AREA

The Sims Bayou watershed is located in south Houston. This watershed has an annual average rainfall of 54.65 in. (NOAA 2010) and poor draining soils composed mainly of fine sandy loams and clay classified under a hydrologic soil group D (University of Houston and Parsons 2009). The watershed lies on the *gulf coast prairies & marshes* natural region of Texas and within the *upland prairies & woods* ecological sub region. The surface is relatively flat with an elevation of 21'- 58' sloping toward the northeast. The watershed has a drainage area of 93.5 $mi^2$.(HGAC 2010). Although the majority of the watershed lies inside Harris County as can be seen in Figure 3, approximately 10.8 $mi^2$ is located inside Fort Bend County. Sims Bayou drains into the Houston Ship Channel (Buffalo Bayou). Both the Houston Ship Channel and Sims Bayou are tidally-influenced (University of Houston and Parsons 2009, HCFCD 2010).

Sims Bayou not only drains the City of Houston but also the cities of Pasadena, Missouri City, and the City of South Houston. It is a highly urbanized watershed with only portions of the middle section of the watershed remaining "undeveloped ranchland" (HGAC 2010). Although the watershed was settled before 1915, the watershed experienced large increases in development in the 1950s and 1970s accompanied by an increase in population. The populations of Houston and Missouri City have increased by 31.6% and 86.2% respectively since 1980 (USCB 2012).

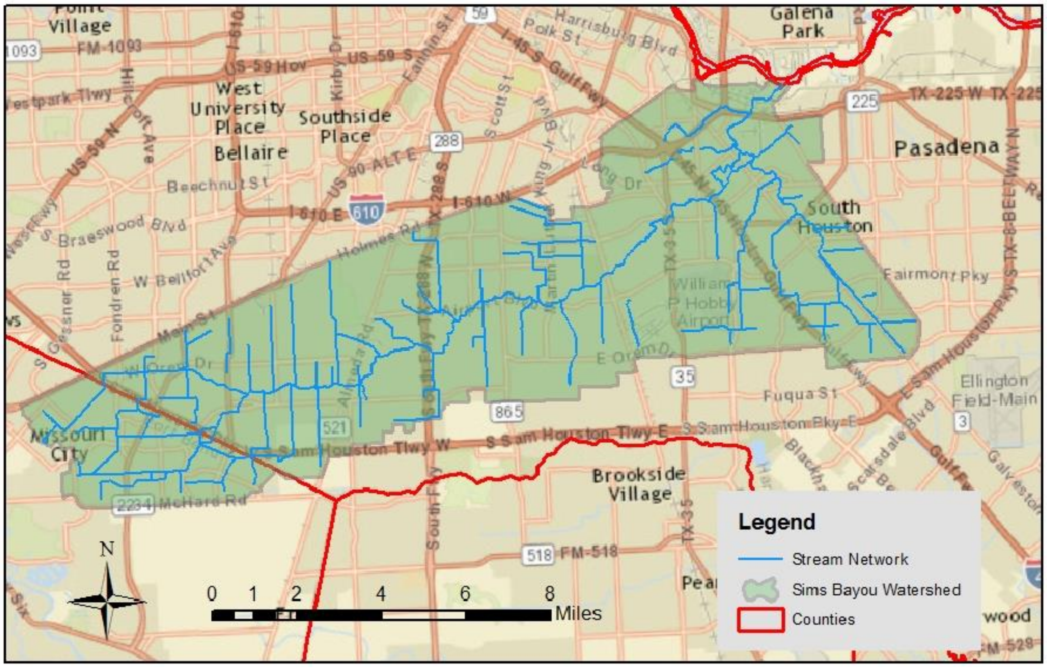



Figure 3- Sims Bayou is the receiving body for numerous channels and natural tributaries such as Berry bayou, Plum Creek, and Pine Gully accounting to approximately 121 miles of open streams.

# 4. METHODOLOGY

The main objective of this research study was to determine the relationship between the urbanization that has occurred in Sims Bayou and the changes in observed flows at the flow gaging stations located on the bayou. To achieve this objective, the methodology used consisted of the following tasks:

## *4.1 Data Acquisition*

The data necessary for this research study was comprised of hydrologic and development records as well as hydrologic and hydraulic models. The data that was used included:

a) Daily and annual total precipitation depths: Precipitation depths were obtained from the National Climatic Data Center (NCDC) of the National Oceanic and Atmospheric Administration (NCDC 2014).

b) Daily average flows and instantaneous maximum annual flows: Flow measurements were obtained from the National Water Information System (NWIS) from the USGS (NWIS 2014).

c) USGS gage locations: The locations of the USGS flow gages were obtained from the USGS NWIS mapper as point shapefiles (NWIS 2014).

d) NOAA surface weather station locations: The locations of the NOAA surface weather station locations was determined from the precipitation data metadata. The longitude and latitude of the stations were used to create point shapefiles. (NCDC 2014).

e) Local hydrography: Local stream network for the area of interest was extracted from the National Hydrography Dataset (NHD) for Harris and Fort Bend counties accessed through the Natural Resources Conservation Service Geospatial Data Gateway. (NRCS 2014).

f) Digital elevation model (DEM): A DEM of the area of interest was extracted from the National Elevation Dataset in the finest resolution available currently (3-meter grid). DEMs were obtained by counties (Fort Bend and Harris) from the Geospatial Data Gateway of the NRCS (NRCS 2014).

g) Parcel data shapefiles and attributes: Parcel shapefiles and tax rolls were obtained from the Harris County and Fort Bend County appraisal districts. HCAD offered all data necessary for download through their website, whereas FBCAD offered their geo-referenced tax information by request free of charge for educational purposes only through CD (HCAD 2014, FBCAD 2014).

h) Local hydrologic and hydraulic models: HEC-HMS and HEC-RAS models and supporting data for the Sims Bayou watershed were obtained from the Model and Map Management System from the Harris County Flood Control District (HCFCD 2008).

### *4.2 Determination of Suitable Precipitation and Flow Stations*

In order to include the periods where the most notable development changes occurred in the watershed, a 40-year period of analysis or greater was desired. This period length would capture the watershed's development of the 1950's or 1970's and would provide the most accurate representation of the watershed's hydrologic behavior in response to development changes. Thus, precipitation and flow stations to be used in this research study were selected by the length of their periods of record as well as by the completeness of their time series. The Sims Bayou watershed has four USGS flow gage stations. However, two of those stations have a limited period of record with only 5 years of data, so they were deemed inadequate for the purposes of this research. The remaining two gages (08075400 and 08075500) provided a time series of discharge with records for at least the last forty years and thus were selected for use in this study. In terms of precipitation, Sims Bayou has two weather stations within the Sims Bayou watershed that provided a precipitation time series with records for the last 40 years or more. The relevant information regarding the flow and precipitation stations selected are summarized in Table 1. Figure 4 displays the locations of the selected precipitation stations and flow gages.

Table 1- Precipitation and discharge stations within the Sims watershed with a period of record of at least 40 years.

| Precipitation stations | | | |
|---|---|---|---|
| Station Name | Station ID | Start Date | End Date |
| Houston Westbury, TX | GHCND: USC00414325 | 1948 | 2014 |
| William P. Hobby Airport, Houston TX | GHCND: USW00012918 | 1941 | 2014 |
| Stream flow stations | | | |
| Station Name | Station ID | Start Date | End Date |
| Sims Bayou at Hiram Clarke St. Houston, TX | USGS: 8075400 | 1964 | 2012 |
| Sims Bayou at Houston, TX | USGS: 8075500 | 1953 | 2013 |

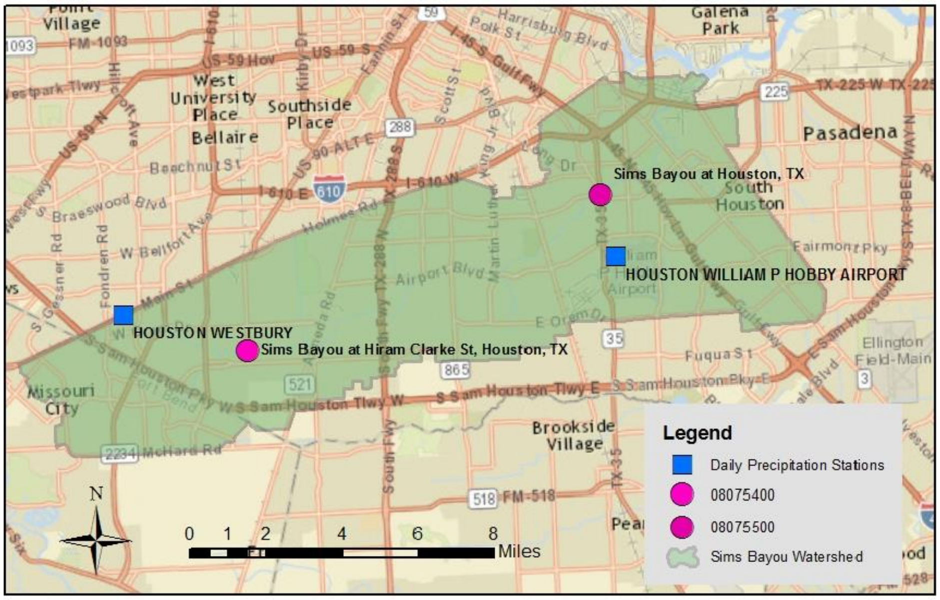



Figure 4- Location of precipitation stations and discharge gages within the Sims Bayou watershed.

### *4.3 GIS-Delineation of Relevant Watersheds*

To determine the spatial extent of the analysis, the watersheds for the selected USGS gages were delineated. GIS hydrology tools were used to delineate the watersheds. These watersheds served as the boundaries for the development data and precipitation volume calculations. Watershed delineation in GIS consisted of two major steps: pre-processing, and delineation. Pre-processing transformed the original dataset into a usable format, and delineation used the output of the pre-processing step in order to delineate the watershed based on elevations.

The original DEM was downloaded in a TIFF format by USGS quadrant, so before the *watershed* tool could be used, the data had to undergo pre-processing. The quadrants were resampled into 3m x 3m grids since the grid for each quadrant had slightly different cell sizes. After resampling, the TIFF quadrants were mosaicked and set to snap to one of the quadrant's corners. The resulting TIFF was then converted into a raster grid using the *Raster to Other* tool. Since the original DEM elevations were in meters and the geographic projection of the raster was not optimal for area calculations for the state of Texas, the *Project Raster* tool used a bilinear interpolation to create a copy of the data in the metric NAD 1983 Texas South Central State Plane projection. This changed the projection of the dataset to have units of meters that matched its elevation units. Additionally, another copy of the mosaicked DEM was saved with the NAD 1983 Texas South Central State Plane projection in feet, and the *raster calculator* tool was used then to transform the elevation values from meters to feet by multiplying the metric grid by 3.2808.

Once the data was projected onto the state plane projection, the *fill* tool was used first to remove small imperfections in the data. After *fill*, the *flow direction* and *flow accumulation* tool were used. In order to reproduce the streams in the watershed, the *stream definition* tool was used. The output of this tool was used in order to snap the USGS gage locations to the closest stream cell. The snapped points along with the flow direction grid were used as the input to the *watershed* tool. Since the two gages were located along the same reach of the bayou, the watershed of one gage is a sub watershed for the other gage and would not be mapped correctly, the tool was run separately for each gage location. As seen in Figure 5, the result was two watersheds of 19.03 $mi^2$ and 62.96 $mi^2$ which served as the outlines for the development analysis.

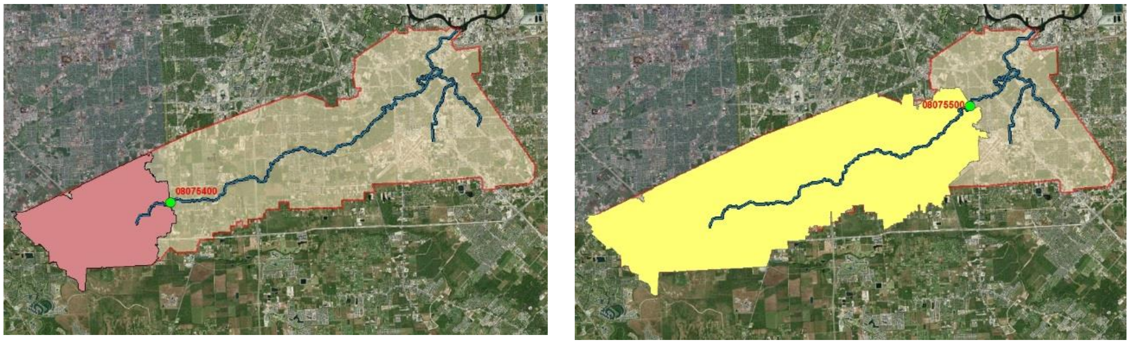



Figure 5- Gages delineated from DEM using (a) USGS gage 08075400 (b) and USGS gage 08075500

### *4.4 Hydrologic Data Processing*

For each of the two flow gage stations, the following steps were taken:

a) <u>Daily precipitation depths and annual peak flow</u>: Daily precipitation and annual peak flow values were used to develop a time series of normalized peak flows. Using cumulative precipitation depths for up to 6 days before the occurrence of peak flow, annual maximum discharges were adjusted to account for precipitation variation. For gage 08075400, peak flow records from 1965 to 2012 were used and for gage 08075500, peak flow records from 1953-2012 were used. Daily precipitation depths for the two weather stations within the Sims watershed were converted from tenths of millimeters to feet. Records from the Westbury station were paired with the peak flow records from gage 08075400 and records from the Hobby Airport station were paired with peak flow records from gage 08075500. Records for the Hobby Airport station were mostly complete with some values missing before the dates of peak flow of 1983 and 1997. Records for the Westbury station had missing values before the dates of peak flow of 1973, 1997, 1998, 1999, and 2000. Years with values missing for any of the 6 days before peak flow occurrence were omitted from the analysis. Additionally, Westbury station records for 9 years showed rainfall depths of 0 inches occurring the day of peak flow and even on days before peak flow occurrence. Since this station was paired with a gage in close proximity and in the upper portion of the stream which could not be experiencing peak flows traveling down from rain elsewhere, these records portrayed an inaccurate representation of the hydrology for the area and were omitted from analysis too. Therefore, from the 47 years of record at the Westbury station, only 33 years were used.

Using these precipitation and peak flow records, cumulative daily precipitation depths were matched with the yearly peak flow for the periods from the day of peak flow to six days before the annual peak flow occurred each year. To reduce the variation in the series caused by varying rainfall depths through time, annual peak flow values were normalized by watershed area and the total precipitation that occurred within a 7-day period prior to and including the day of peak flow occurrence. The 7-day period consisted of days numbered 0 to 6 with day 0 being the day in which peak flow occurred and day 6 being the $6^{th}$ day prior to peak flow occurrence. The peak flows were normalized by seven different precipitations corresponding to the total precipitation measured at the weather station from day *n* prior to and including the day of peak flow occurrence. Thus, for example for period 2, the annual peak flow was normalized by all rainfall measured starting two days before peak flow occurred and including the day of peak flow occurrence (total of 3 days). In the case of gage

08075500, since there were only a couple of missing values in the resulting normalized dataset due to missing precipitation values, values for the year before and after the missing value were used to interpolate a maximum possible runoff in their place. For gage 08075400, there were too many years with missing values, so those years were omitted completely.

A series of seven graphs were produced for each gage as seen in Figure 6 and 7 for gages 08075400 and 08075500 respectively. The smallest variability as measured by the range of normalized values was seen by using the cumulative depths occurring 6 days before the yearly peak flow as expected. For both gages, records for the yearly peak flows normalized by maximum possible runoff generated within the seven time periods were smoothed by using a moving average of order five. In this case, too, the moving average of the records showed that peak flows normalized by the seven-day rainfall depth had the least variability. Smoothed time series for the seven-day rainfall for both gage 08075400 and 08075500 are shown in Figure 8. Although smoothing did reduce variability, the overall positive trends remained visible in both unsmoothed and smoothed graphs using maximum possible runoff generated from rainfall occurring up to 6 days prior to peak flows.

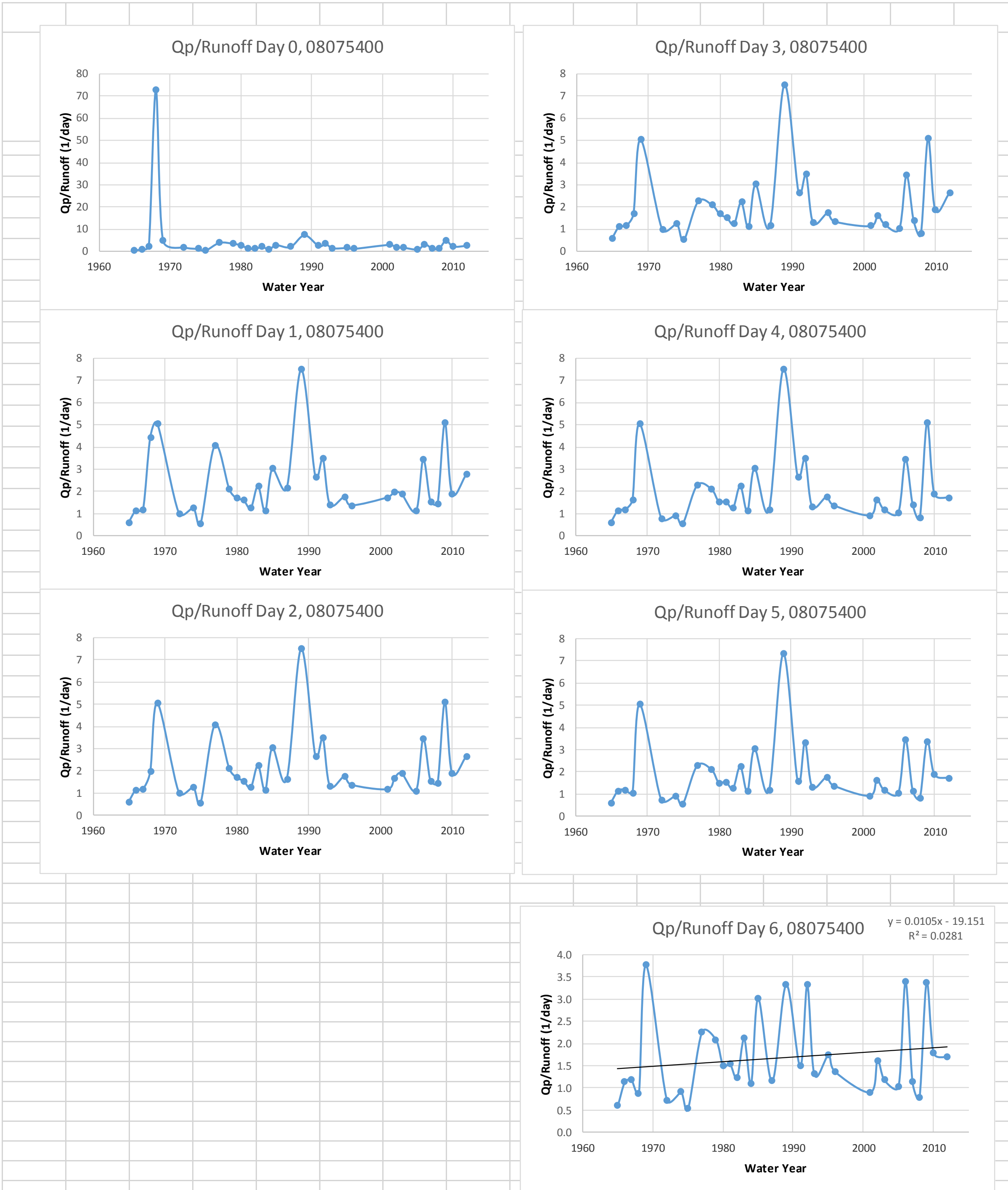



Figure 6 - Annual peak flows normalized by maximum possible runoff generated from day of to 6 days before peak flow occurrence for gage 08075400

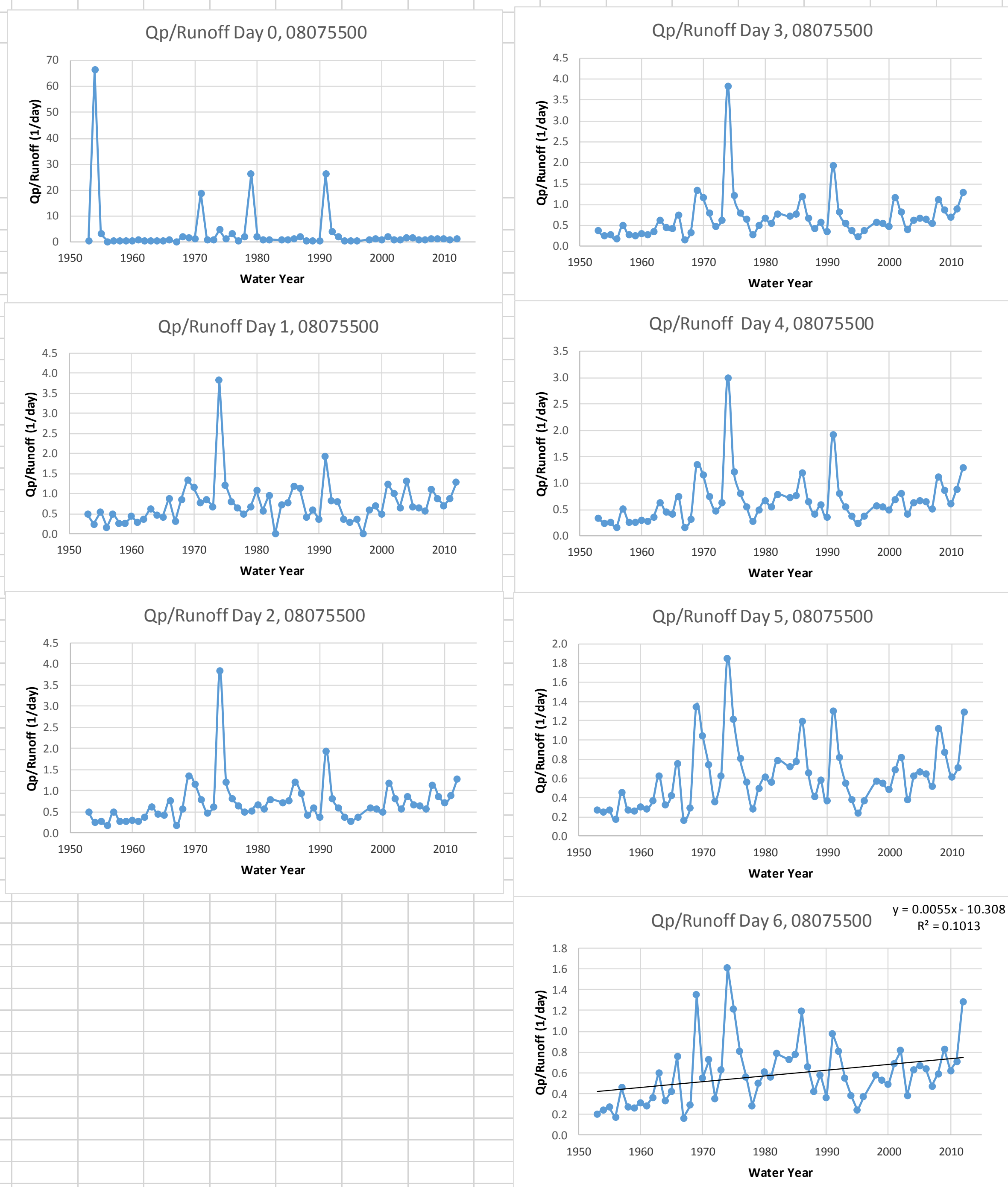
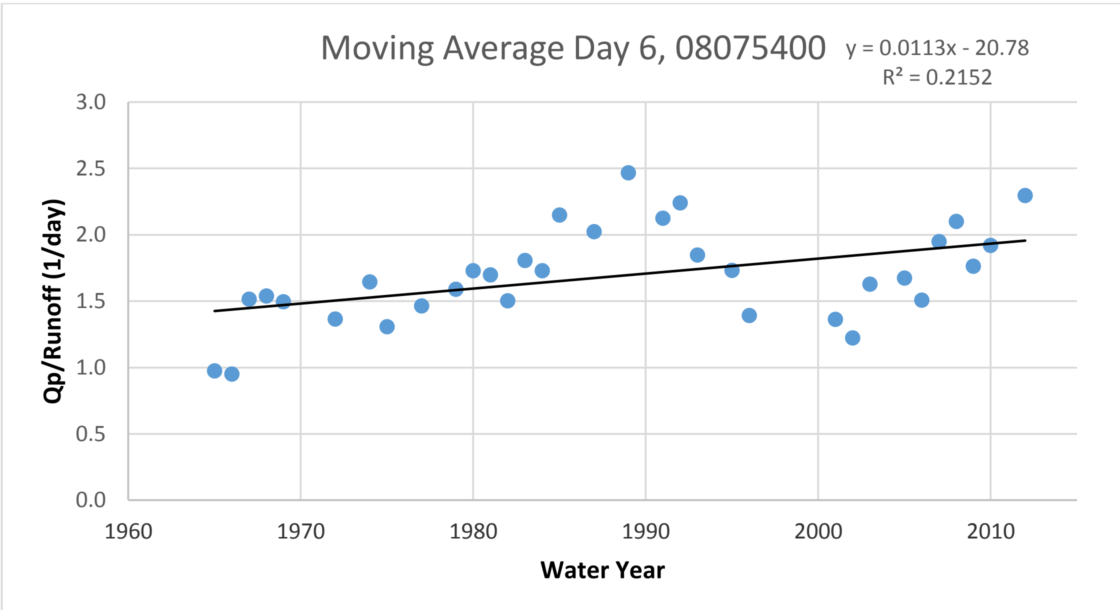
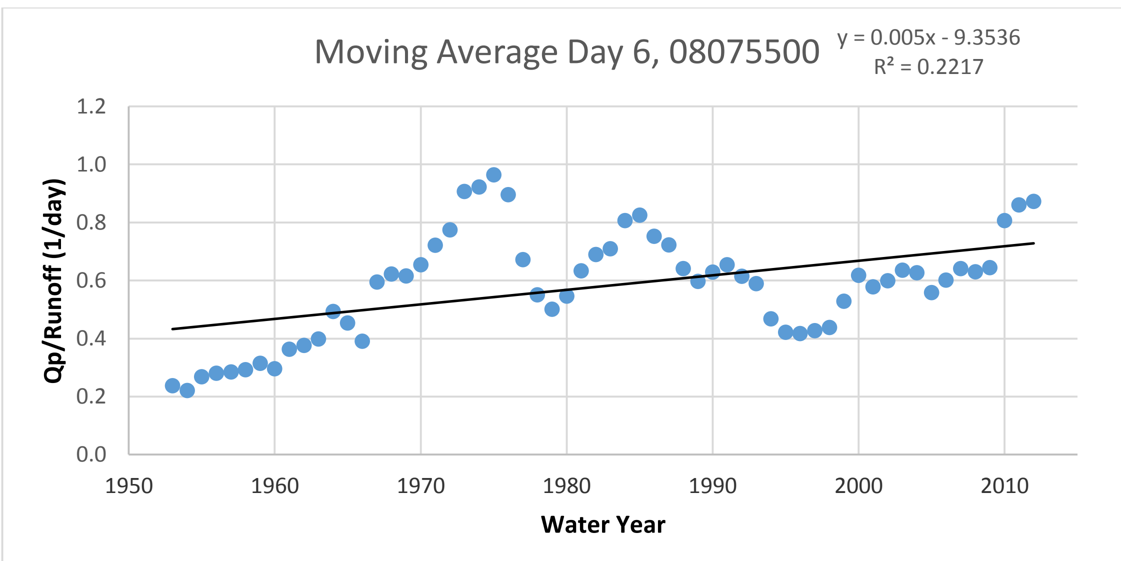



Figure 7- Annual peak flows normalized by maximum possible runoff generated from day of to 6 days before peak flow occurrence for gage 08075500




(a)




(b)

Figure 8 - Moving Average of order five of annual peak runoff normalized by maximum possible runoff generated within 6 days of peak flow occurrence for gage (a) 08075400, and (b) 08075500

b) Annual precipitation depth and daily average flow: Since the annual precipitation depths for the two stations was expected to be very similar, only the records of the Hobby Airport station were used in this research. Annual depths were obtained by summing the monthly precipitation totals in hundredths of inches and converting them into inches. The records were mostly complete with four years having up to two missing months which were recreated by averaging the records for the same months for the previous and following two years. These years were 1990, 1995, 1999, and 2005. Another four years had too many months to recreate the data. These years were 1948, 1951, 1956, and 1998. The annual precipitation depths were then converted into annual precipitation volumes by Eq 1 below:

$$V_P = \frac{P_d}{12} \times A \qquad (1)$$

Where:

$V_P =$ Volume of precipitation that contributes to flow measured at USGS gage, ft$^3$

$P_D =$ Annual precipitation depth measured at weather station, inches

$A =$ Area of watershed that contributes to flows measured at USGS gage, ft$^2$

Records for daily average flows for gage 08075400 were available from 1964 to 2012. Records for daily average flows for gage 08075500 were available from 1952 to 2001. For both gages, years which had more than 15% missing daily average flow values were omitted. For both gages, eight years in each gage were removed from the analysis. Years in which there was less than 15% missing values (only 1978 for gage 08075400) were kept and data for the days missing was recreated by averaging discharge values for those days in the prior and following two years. After filling in for missing values, the daily average flows were converted into daily volumes by the use of Eq. 2. As seen in Eq. 3, the sum of the daily volumes by year yields the annual runoff of the watershed.

$$V_D = Q_d \times 86400 \quad (2)$$

$$\sum_{i=1}^{j} V_D = V_Y \quad (3)$$

Where:

$V_D$ = Average daily volume of water measured at USGS gage, $ft^3$

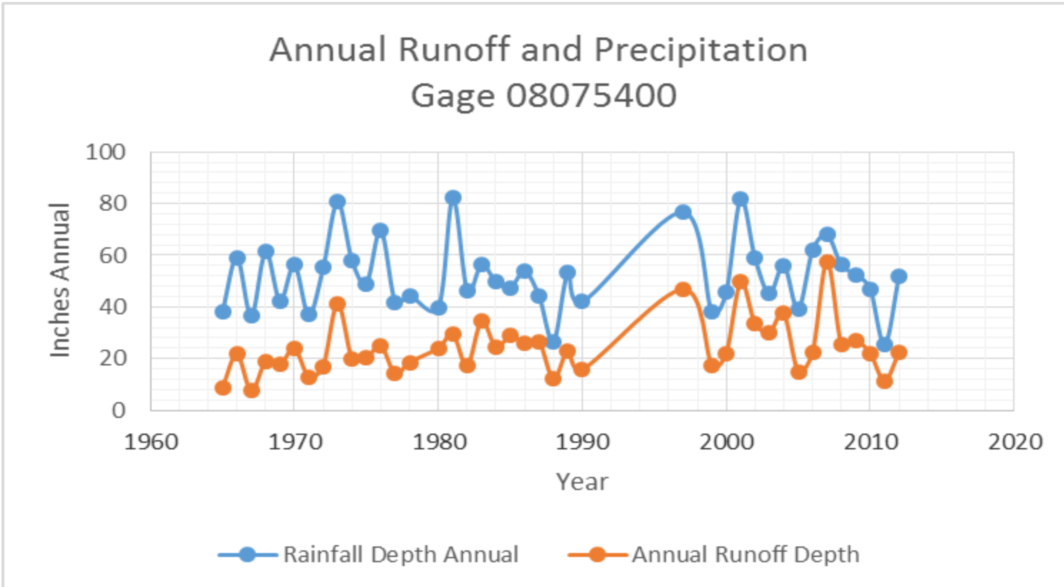
$Q_d$ = Average daily stream flow measured at USGS gage, $ft^3/s$

$V_Y$ = Yearly volume of water passing through USGS gage, $ft^3$

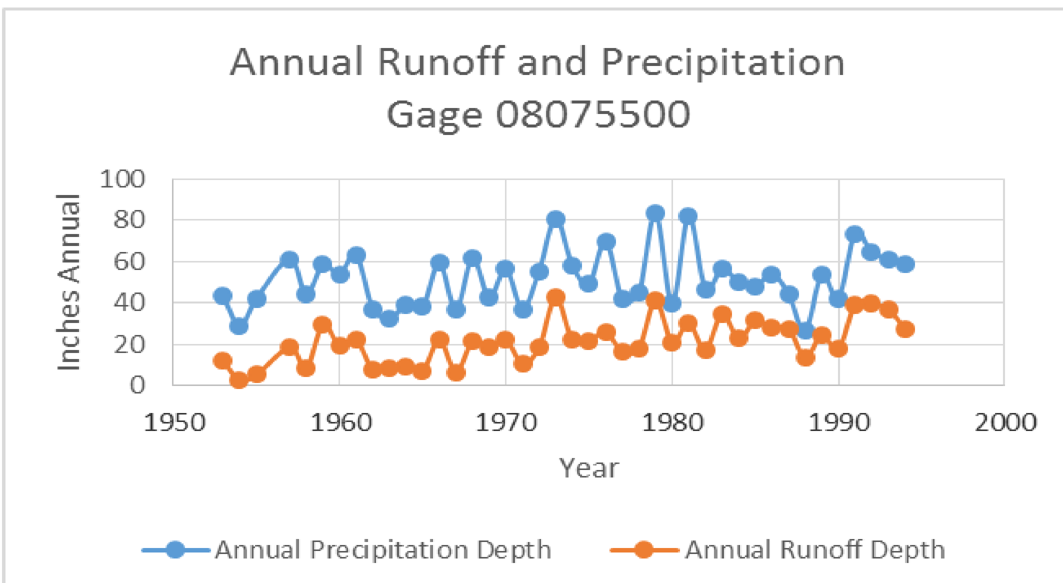
$i$ = First day of the year

$j$ = Last day of the year (365/366)

In Figure 9 below, the annual runoff volume of the watershed, $V_Y$, and the annual precipitation volume, $V_P$ , for every year in the period of record were graphed for each gage to verify that both the precipitation and runoff series had similar characteristics. Mostly, both series had very similar shapes with a few inconsistencies such as higher than expected runoff for 1980 and 2007 in gage 08075400, and lower than expected runoff for 1974 and 1981 in gage 08075500.



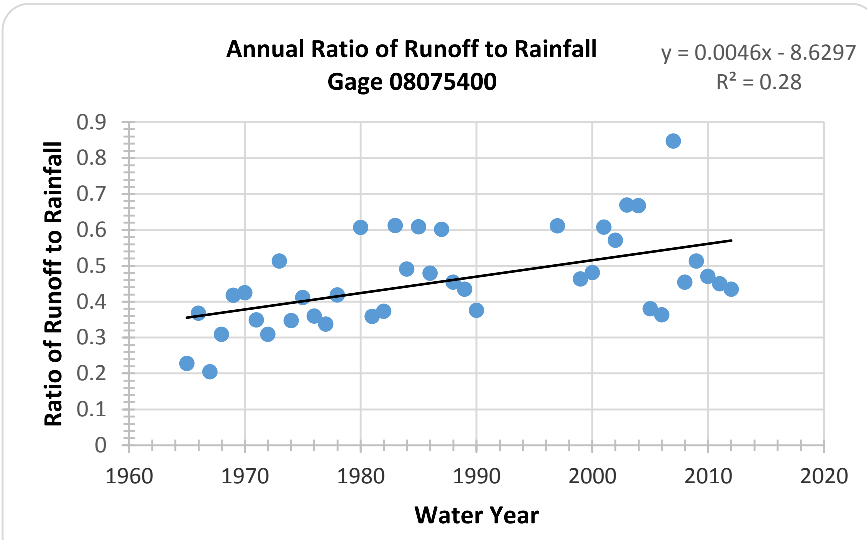
(a)



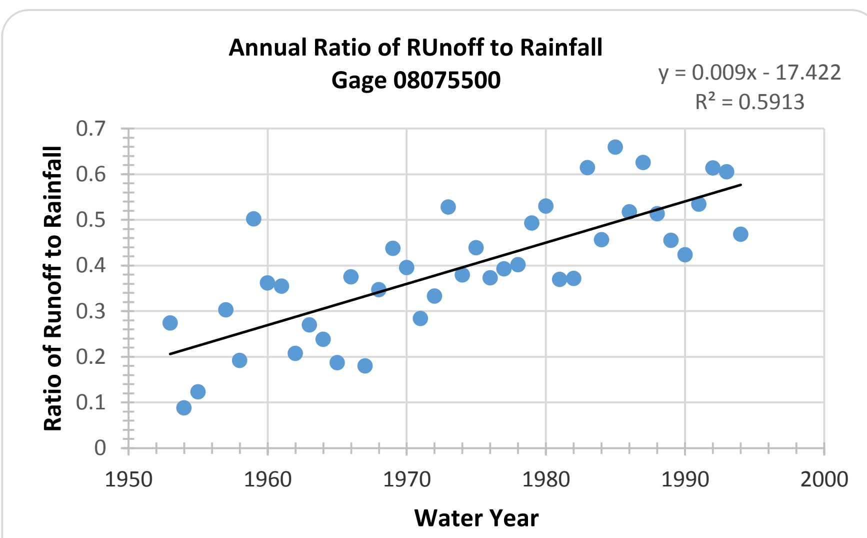
…
(b)

Figure 9- Comparison of annual precipitation and runoff from the two gages at Sims Bayou, (a) 08075400, and (b) 08075500

The annual runoff of the watershed, $V_Y$, was then divided by the annual precipitation volume, $V_P$ , for every year in the period of record for each gage and plotted against time in Figure 10. The dependent variable was changed from time to percentage of development once development maps were created.




(a)




(b)

Figure 10-Ratio of annual runoff to rainfall through time for gage (a) 08075400 and (b) 08075500

### *4.5 GIS- Yearly Development/Impervious Cover Maps*

Since the Sims Bayou watershed is located on both Harris and Fort Bend counties, property tax information from both counties were used. The data of interest from the appraisal districts consisted of geo-referenced parcel shapefiles, and parcel attributes such as parcel size, building footprint, parcel built date, improved value, and land value. For Harris County, account information with the necessary attributes was available as text files that were imported into a template Microsoft Access database (also available from HCAD's website). Account data was split into several database tables and categories, but for this research study only the "Real_Building" category was used. Within this category, the tables "building_other" and "building_res" were imported into GIS and merged. Tables containing information on previous ownership and parcel changes, exemption types, property tax hearings and protests, building exterior characteristics, and personal property were not used for this study. The resulting table was joined to the HCAD parcels shapefile using the "Account" field. A copy of the resulting join was exported and saved separately. For Fort Bend, parcel and account information were already joined and did not require a similar process. However, FBCAD's roads were assigned parcels with a built year of zero. HCAD does not map road easements so there were no road parcels. Thus, for consistency and to assign the roads a built year, the road parcels in FBCAD's data were removed. The data also presented other inconsistencies such as not having a built date for parcels which were clearly built as confirmed by aerial photography, not having a correct building footprint, and having several condominiums mapped onto the same polygon. To address these inconsistencies, several steps were taken.

First, a sample of parcels showing no built date (excluding roads) were chosen. Those parcels were separated into subbasins and were classified into developed or undeveloped categories using the GIS imagery basemap. The subbasins used for analysis were those from the HEC-HMS model obtained from HCFCD. For each subbasin, the number of developed and undeveloped parcels were counted and a percentage of developed parcels was determined. The percent of developed parcels within each sub watershed was used to determine an average percent developed for parcels with no built date. This average was used in randomly selecting a number of the parcels without a built date within the watershed. Parcels without a built date corresponding to roads, properties owned by the HCFCD, parcels bigger than 20 acres, or parcels that had a vacant designation by state classification were not included in the selection. The selected parcels were then assigned a built year that matched the newest constructed property in a 500 ft. radius. A similar procedure was used to assign built dates to road polygons. Road polygons were first created by intersecting a fishnet of 50 ft. grids with the gaps in the parcel maps. From these polygons, the polygons corresponding to the drainage network from the NHD were removed. Then, the road polygons were assigned a built date that matched the oldest constructed property in a 150 ft. radius.

Secondly, since the FBCAD parcels did not have a base area or a field with the number of stories for the property, a footprint area for each parcel was assigned onto a new field called “Imp_AREA”. The footprint area was assigned based on the

“TOTSQFTLVG”, “IMPSIZEFT”, and “ImpMainSeg” fields. The “IMPSIZEFT” field included improved areas that were part of the structure itself as well as some patios, whereas the ‘TOTSQFTLVG” field had only the total area of the structure. The “ImpMainSeg” field contained a code that includes the number of stories of the building as a number at the end of the code, so the query builder was used to systematically select Fort Bend parcels which had values in the “ImpMainSeg” ending with a designated number. For the selected parcels with a number, N, of stories, the “Imp_AREA” field was populated by using with Equation 4:

$$\mathrm{Imp\_AREA} = \mathrm{IMPSIZEFT} - \frac{(N-1)}{N} * \mathrm{TOTSQFTLVG} \;\ldots\ldots\; (4)$$

To assign built areas to the parcels without a built date, a new field was added to calculate the improvement ratio. The improvement ratio represents the percentage of the parcel that has been improved according to tax rolls, ranging from 0 to 1. The improvement ratio was calculated by dividing the improved area by the parcel area using the newly created “Imp_AREA” field for FBCAD parcels and the “ACTUAL AREA” field for HCAD parcels. Average improvement ratios were developed from the parcels with original built dates and were applied to assign parcels a building footprint based on their state classification code. Average improvement ratios per state classification code are summarized in Table 2 below.

Table 2- Improvement Ratio applied to selected parcels without a built date

| State Classification Code | Average Improvement Ratio |
|---|---|
| A1 | 0.2668 |
| A2 | 0.1587 |
| A3 | 0.3932 |
| A4 | 0.4634 |
| B2 | 0.3336 |
| E3 | 0.0001 |
| F1 | 0.3138 |
| F1H | 0.0256 |
| F2 | 0.2292 |
| X1 | 0.0666 |
| X2 | 0.4021 |
| X3 | 0.2152 |
| X4 | 0.0000 |

Thirdly, accounts for condos were mapped as stacked parcels with most of them showing no parcel size. This would yield errors when calculating an improvement ratio. After analyzing these accounts, the bulk of the accounts are accounted for by 25 properties with usually at least one account per property having a parcel size. Thus, the condo accounts that did not have a parcel size were assigned a built year of 9999 so that the property was not be counted multiple times in improved area calculations. In other occasions, parcels showed a higher improvement size than parcel size. After inspection of these parcels with the GIS Imagery basemap, although classified as single-family homes, the construction type present in the parcels was more akin to apartment or townhome complexes built over several parcels. Thus, the improvement ratio for these accounts was altered to be 1 and the improved area was changed accordingly.

After the inconsistencies were addressed, the yearly development maps were made by using the outline for each watershed of the USGS gages and the outline for the Sims

Bayou watershed obtained from the HCFCD as boundaries to select all the parcels within them. As parcels within each watershed boundary were sorted by built year, they were exported and saved for each watershed. Parcel built dates were assumed to represent the earliest development in the parcel and no previous development was accounted for. Use of the built dates also assumed that once developed, a parcel was not restored to undeveloped land. Sorting of parcels yielded a time series of the state of development during the period of analysis. A snapshot of the development at the beginning and end of the period of analysis for each watershed that can be seen in Figures 11 and 12 for the watersheds for gage 08075400 and 08075500 respectively. For the watershed for gage 08075400, the percentage of developed area increased from 15.9% in 1965 to 71.1% in 2012 while for the watershed of gage 08075500, percentage of developed area increased from 11.6% in 1953 to 50.5% in 1994.

After yearly development maps were developed for the watersheds of the two USGS gages, development percentage and percentage impervious cover replaced time in the horizontal axis of the Annual Runoff graphs. As seen in Figures 13 and 14, for both gages the relationship between percentage of developed area and ratio of annual runoff to rainfall was stronger than using time as the horizontal axis, and the relationship between percentage impervious cover and the ratio of annual runoff to rainfall was even stronger than using percentage developed area.

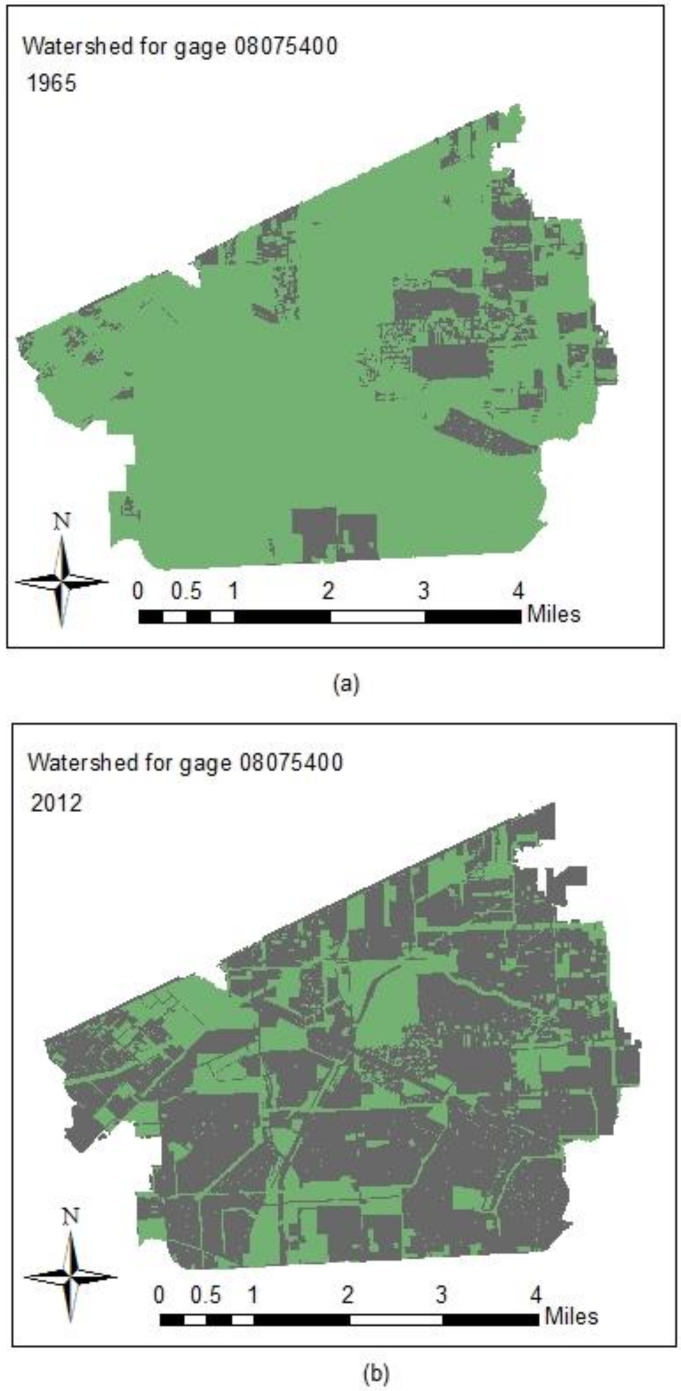
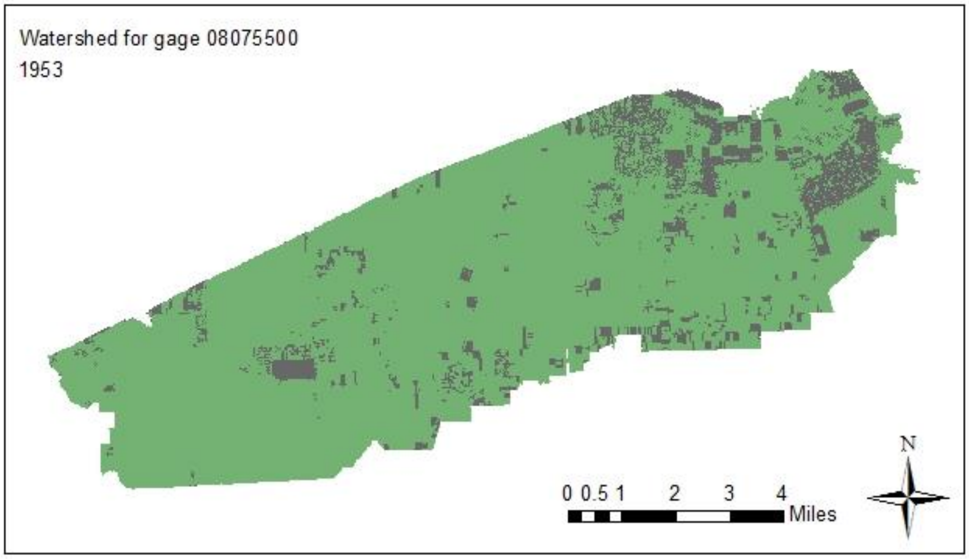
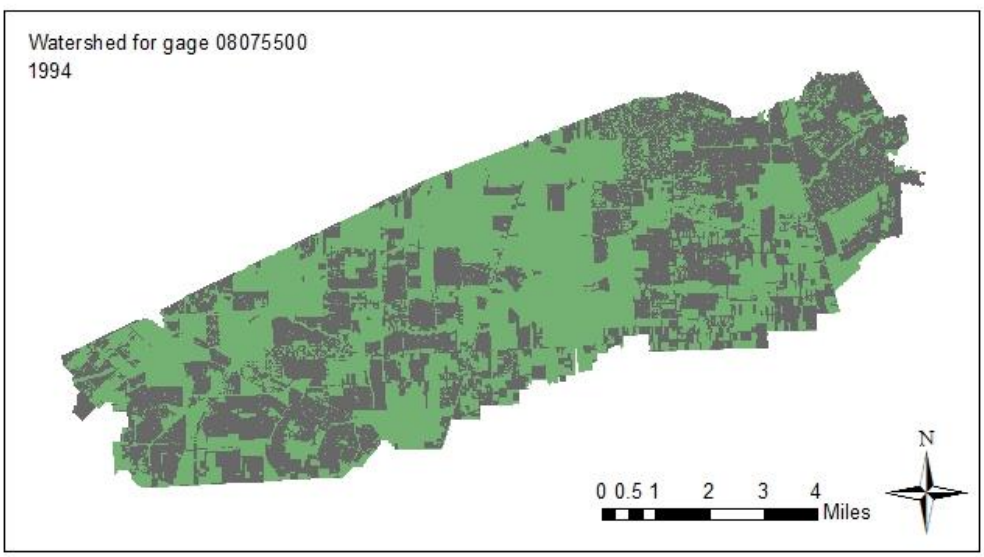



Figure 11- State of development in the watershed for USGS gage 08075400 for (a) the beginning of the period of streamflow records, and (b) at the end of the period of streamflow records

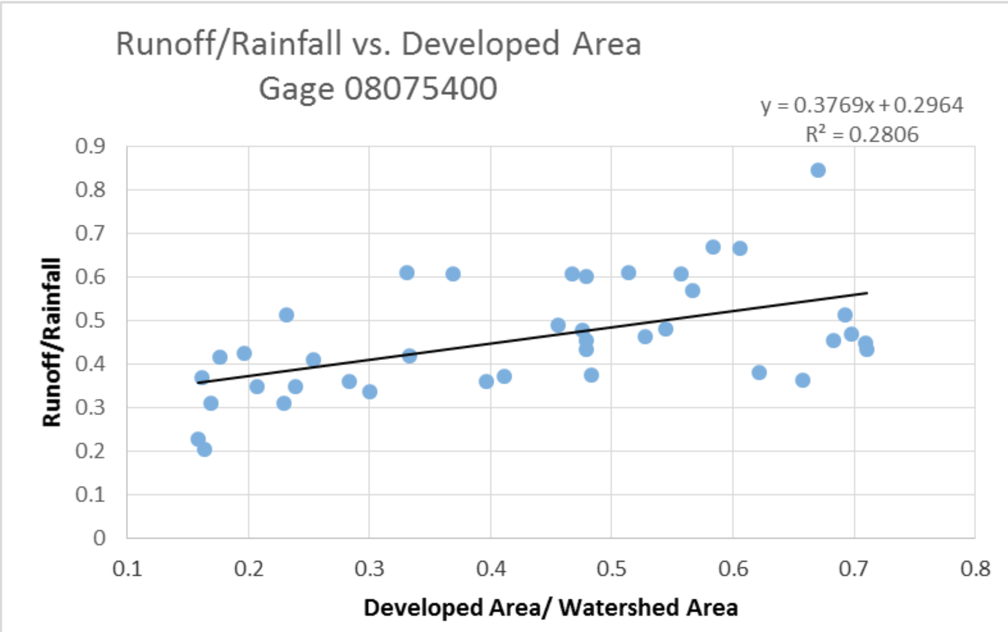



(a)

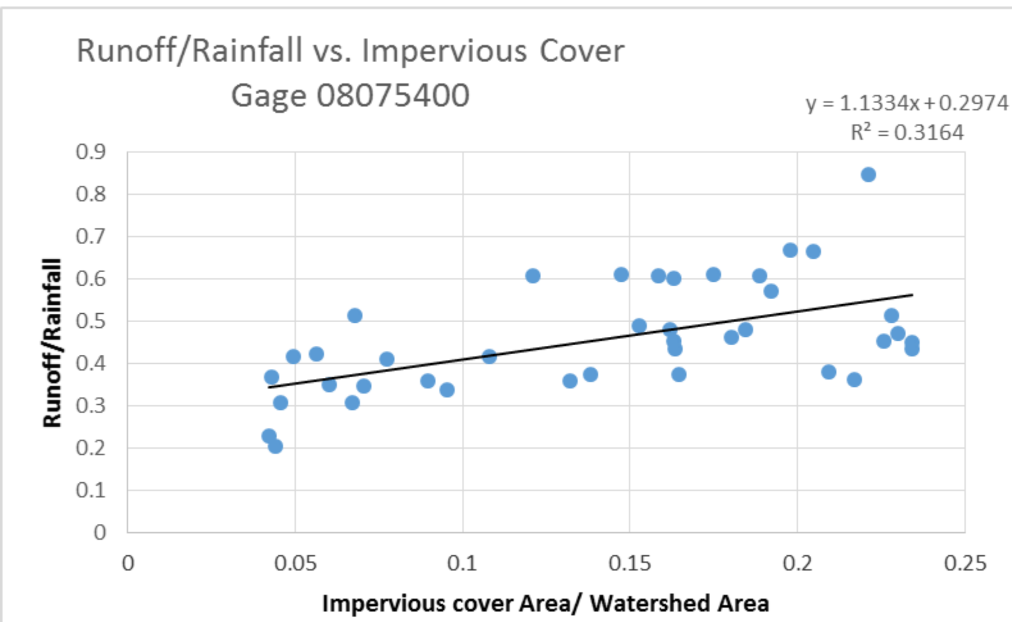



(b)

Figure 12- State of development for the watershed of USGS gage 08075500 for (a) the beginning of period of streamflow records, and (b) the end of period of streamflow records

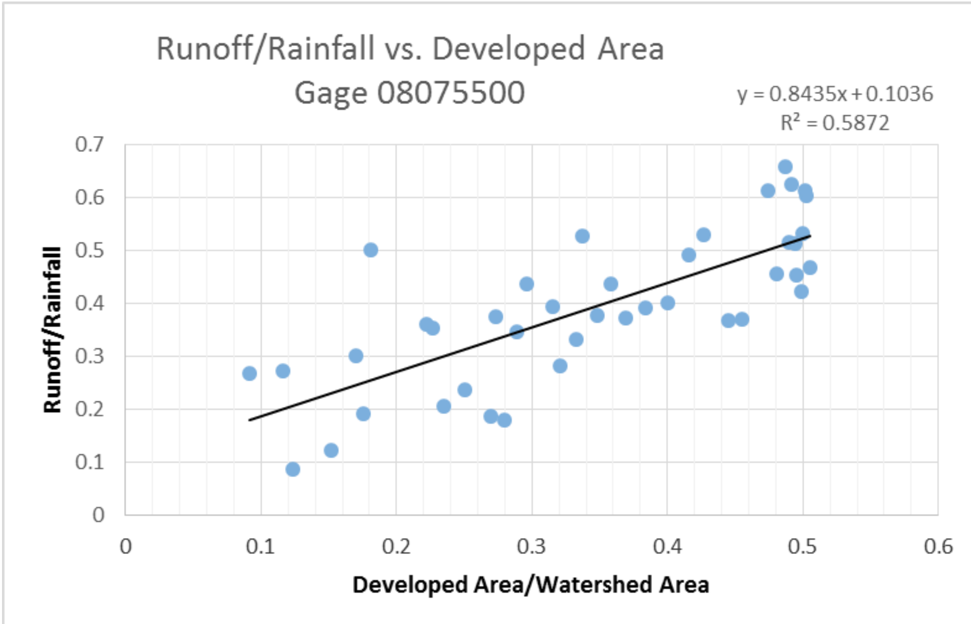



(a)

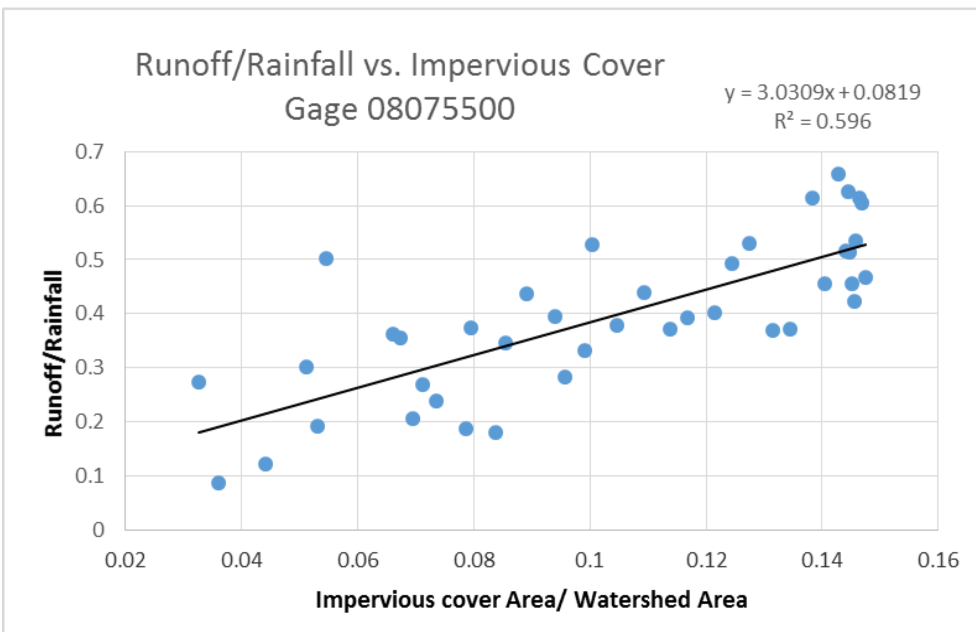



(b)

Figure 13- Positive relationship between ratio of annual runoff to rainfall for gage 08075400 and (a) percentage developed area, and (b) percentage impervious cover




(a)




(b)

Figure 14- Positive relationship between the ratio of annual runoff/rainfall for gage 0807500 with (a) percentage development and (b) percentage impervious cover

### *4.6 Statistical Analysis*

To determine if the flows are significantly different through time, a non-parametric ANOVA was used on decades of flow. Annual peak flows for each gage were grouped into decades. Decades with more than 2 years missing were removed from the analysis. For gage 08075400, peak flows for the decades of 1960 and 2010 were removed and for gage 08075500, peak flows for the decades of 1950 and 2010 were removed. The remaining decades in each gage were analyzed using a Levene test for variance and since the distribution of peak flows was not normal, a Kruskal-Wallis nonparametric test for means was used. For gage 08075400, both the Levene and Kruskal-Wallis test yielded p-values above a significance level of 0.05. These results imply that at the 0.05 level of significance, the variances and means of the peak flows by decades from the 1970's to 2000's are not significantly different. For gage 08075500, however, the Levene test yielded a value lower than 0.05 level of significance, whereas the Kruskal-Wallis test yielded a p-value just above significance. These results imply that although the variances of peak flows per decades from 1960's to 2000's is significantly different, the means of peak flows per decade for the same periods are not. Yet, the p-value from the Kruskal-Wallis test is 0.008 above significance level, and thus the result for difference of means among decades is questionable given the inferior strength of non-parametric tests.

A similar analysis was performed for the daily average flows for each gage. After sorting the daily flows into decades and removing decades with more than 2 years of flows missing, the Kruskal-Wallis test was used to test for a difference in means in average daily flow among decades. For gage 08075400, average daily flows for the decades of 1960's and 1990's were removed. For gage 08075500, average daily flows for the decades of 1950's and 1990's were removed from the analysis. A Levene test was not used for daily flows since the previous hydrologic analysis did not use daily flows directly, but rather annual runoff. Since annual runoff aggregates many daily flows, changes in variance of daily flows between decades may not be seen once aggregated since excesses will make up for shortages throughout the year. So, even if the variances in daily flows changed throughout decades, it may not signify a marked change in annual runoff. For both gages, the Kruskal-Wallis test yielded very small p-values of less than 0.0001. Using a 0.05 significance level, the small p-values imply that the average daily flows by decades along Sims Bayou are significantly different for both of the gages. The distribution is also visibly different by decade. The 75$^{th}$-percentile of flows for both gages consistently increased each decade implying that higher flows occurred more often every decade. Table 3 summarizes the results of the statistical tests used on the flow records, and Table 4 displays the 1$^{st}$ and 3$^{rd}$ quartiles of flows per decade.

Table 3- P-values for statistical tests on peak flows and daily flows for gages 08075400 and 08075500

| Gage | Peak Flow | | Daily Flow |
|---|---|---|---|
| | Levene | Kruskal-Wallis | Kruskal-Wallis |
| 8075400 | 0.1068 | 0.2718 | <0.0001 |
| 8075500 | 0.019 | 0.0576 | <0.0001 |

Table 4- First and Third Quartiles of the distribution of average daily flows for gages 08075400 and 08075500

| Decade | 25th percentile | | 75th percentile | |
|---|---|---|---|---|
| | 8075400 | 8075500 | 8075400 | 8075500 |
| 1960s | | 11 cfs | | 26 cfs |
| 1970s | 7.4 cfs | 24 cfs | 15 cfs | 60 cfs |
| 1980s | 12 cfs | 43 cfs | 20 cfs | 72 cfs |
| 1990s | | | | |
| 2000s | 8.2 cfs | | 22 cfs | |

### *4.7 Hydrologic Modeling with HEC-HMS*

Since the most relevant flood zone for residents of the watershed is the regulatory floodplain (100-year floodplain) due to its importance in the implementation of the National Flood Insurance Program (NFIP), local flood risk reduction programs, and building codes, changes to the regulatory floodplain were selected as the indicator for degree of impact to the community. Because of its importance to developers, policy makers, government officials, and insurance agents among others, the FEMA flood insurance studies, digital FIRMs, and their supporting hydrologic and hydraulic models are available to the public. The HCFCD is the local entity responsible for the official models used to create the FIRM maps currently in effect for the Houston area. To assess the impact of increasing flows along Sims Bayou, the hydrologic and hydraulic models were obtained from the HCFCD and modified to reflect three stages of development in the watershed: 1980, 1990, and 2000.

The Hydrologic model for the Sims Bayou watershed consisted of one watershed with 39 subbasins varying in size from 0.97 mi.$^2$ to 6.27 mi.$^2$ (Figure 15). Each subbasin had different characteristics representing soil types, infiltration characteristics, and impervious cover. The model used rainfall depths associated with a number of recurrence intervals based on USGS report 98-4044, the Green & Ampt equation for infiltration calculations, and the Clark Unit hydrograph for developing a hydrograph from runoff at each subbasin. The 1% exceedance probability storm rainfall hyetograph and the soil characteristics were left unchanged in the model. Since the independent variable of interest was development, only the impervious cover percentages and Clark Unit hydrograph parameters were modified. Hydrograph parameters were modified as a result of changing the percent of development (DLU) in each subbasin.

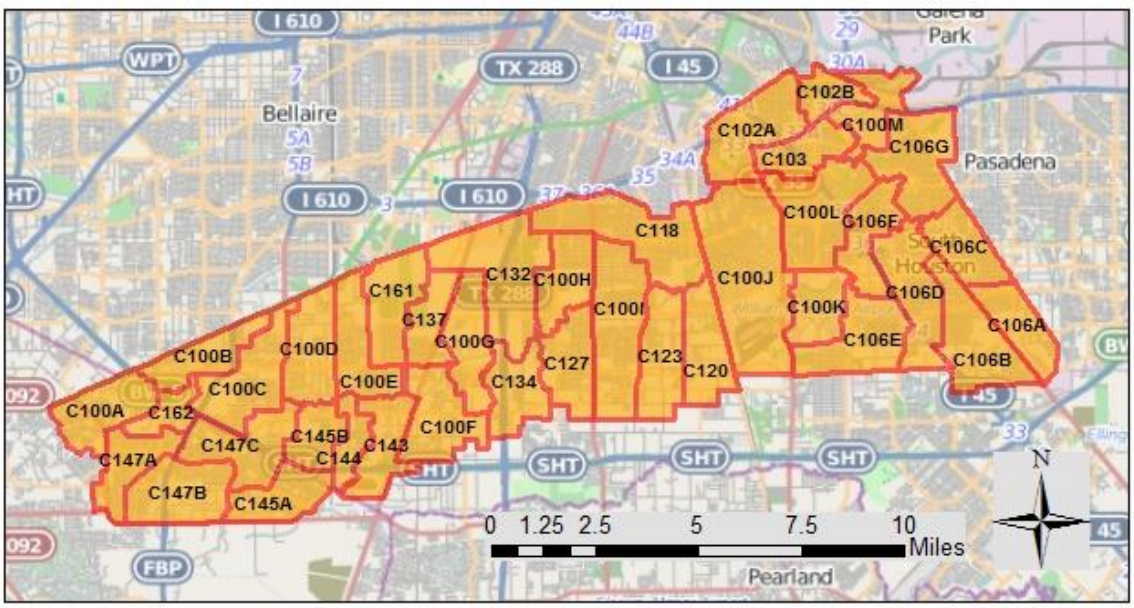



Figure 15-Subbasins of the Sims Bayou watershed in Houston, TX as provided by the HCFCD model and map management system

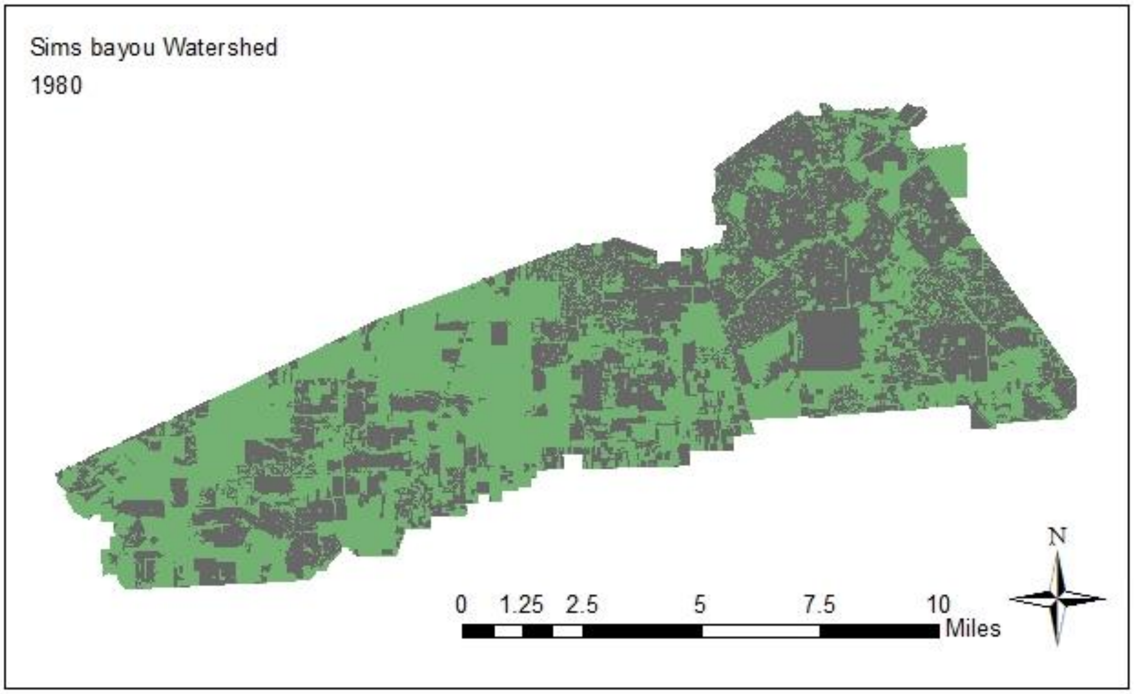
The Clark Unit hydrograph has two parameters which are dependent on various development characteristics such as development percent, developed area served by a detention facility, and minimum development. There were various other parameters included in the calculation of the time of concentration and storage coefficient of the Clark unit hydrograph method that included watershed characteristics like watershed slope and watercourse length as well as improvement characteristics such as percent channel improvement, percent channel conveyance, on-site detention, and percent ponding (Figure 16). Values for all parameters used were provided per subbasin with the model. Although the values for the improvement characteristic parameters may have certainly changed in time, only change in development and impervious cover were analyzed in this research. Changes in percent development (DLU) affect the time of concentration in the Clark Unit hydrograph. Changes in impervious cover percentage do not affect the hydrograph parameters, but rather the loss rates. As the percentage of developed area changed in the three stages of development (1980, 1990, and 2000), the parameters for the Clark Unit hydrograph also changed for each subbasin. Using the yearly development maps for the Sims Bayou watershed and intersecting it with the subbasin boundaries, development and impervious cover percentages for each subbasin were determined for 1980, 1990, 2000, and 2002. Figure 17 shows the state of development in 1980 and 2000. The development map for 2002 was created to compare development and impervious cover values derived by parcel data with the values on the model since model values were determined using HCAD data from 2002 and aerial photography.

<table>
<tr><th></th><th colspan="2">Process</th></tr>
<tr><td>1</td><td colspan="2">Determine L, $L_{CA}$, S, $S_O$, DLU, DCI, DCC, DPP and DET</td></tr>
<tr><td>2</td><td colspan="2">Calculate $DLU_{minimum} = 11344(DCC)^{-1.4049}$</td></tr>
<tr><td>3</td><td colspan="2">Calculate $DLU_{detention}$ and TC and R with one of the following equations</td></tr>
<tr><td></td><td>IF…</td><td>THEN…</td></tr>
<tr><td></td><td>$DLU – DET \geq DLU_{minimum}$</td><td>• $DLU_{detention} = DLU – DET$<br>• $TC = D[1 – (0.0062)(0.7\,DCI + 0.3\,DLU_{detention})](L_{CA}/\sqrt{S})^{1.06}$<br>• $TC+R = 4295(DLU_{detention})^{-0.678}(DCC)^{-0.967}(L/\sqrt{S})^{0.706}$</td></tr>
<tr><td></td><td>$DLU > DLU_{minimum}$<br><u>AND</u><br>$DLU\text{-}DET < DLU_{minimum}$</td><td>• $DLU_{detention} = DLU_{minimum}$<br>• $TC = D[1 – (0.0062)(0.7\,DCI + 0.3\,DLU_{minimum})](L_{CA}/\sqrt{S})^{1.06}$<br>• $TC+R = 4295(DLU_{minimum})^{-0.678}(DCC)^{-0.967}(L/\sqrt{S})^{0.706}$</td></tr>
<tr><td></td><td>$DLU < DLU_{minimum}$</td><td>• $DLU_{detention} = DLU$<br>• $TC = D[1 – (0.0062)(0.7\,DCI + 0.3\,DLU)](L_{CA}/\sqrt{S})^{1.06}$<br>• $TC+R = 7.25(L/\sqrt{S})^{0.706}$</td></tr>
</table>

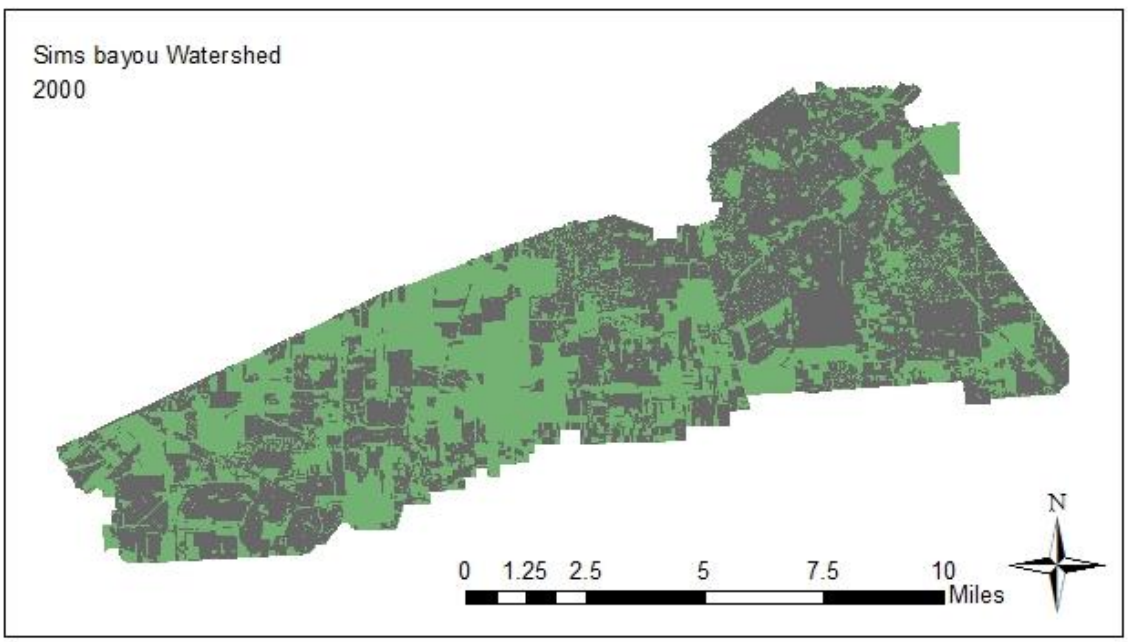
Where:

| | | |
|---|---|---|
| $DLU_{minimum}$ | = | $11344(DCC)^{-1.4049}$ |
| L | = | watershed length in miles |
| $L_{CA}$ | = | length to centroid in miles |
| S | = | channel slope in feet per mile |
| DLU | = | percent urban development |
| DCI | = | percent channel improvement |
| DCC | = | percent channel conveyance |
| D | = | Watershed slope factor<br>• 2.46 if $S_O \leq 20$ feet/mile<br>• 3.79 if 20 feet/mile $< S_O \leq 40$ feet/mile<br>• 5.12 if $S_O > 40$ feet/mile |
| $S_O$ | = | watershed slope, in feet per mile |

Figure 16- Procedure for determining Tc and R for HCFCD HEC-HMS model, extracted from HCFCD Hydrology and Hydraulics Manual




(a)




(b)

Figure 17- State of development in the Sims Bayou watershed in (a) 1980 and (b) 2000

Upon comparison of the values per subbasin from the model and the maps, it was apparent there was a discrepancy between values in the model and the values obtained through this study. From Figure 18, it is visible that although the percent developed area per subbasin was generally close to that of the model, the impervious cover percentage was higher in the model than values derived using the development maps.

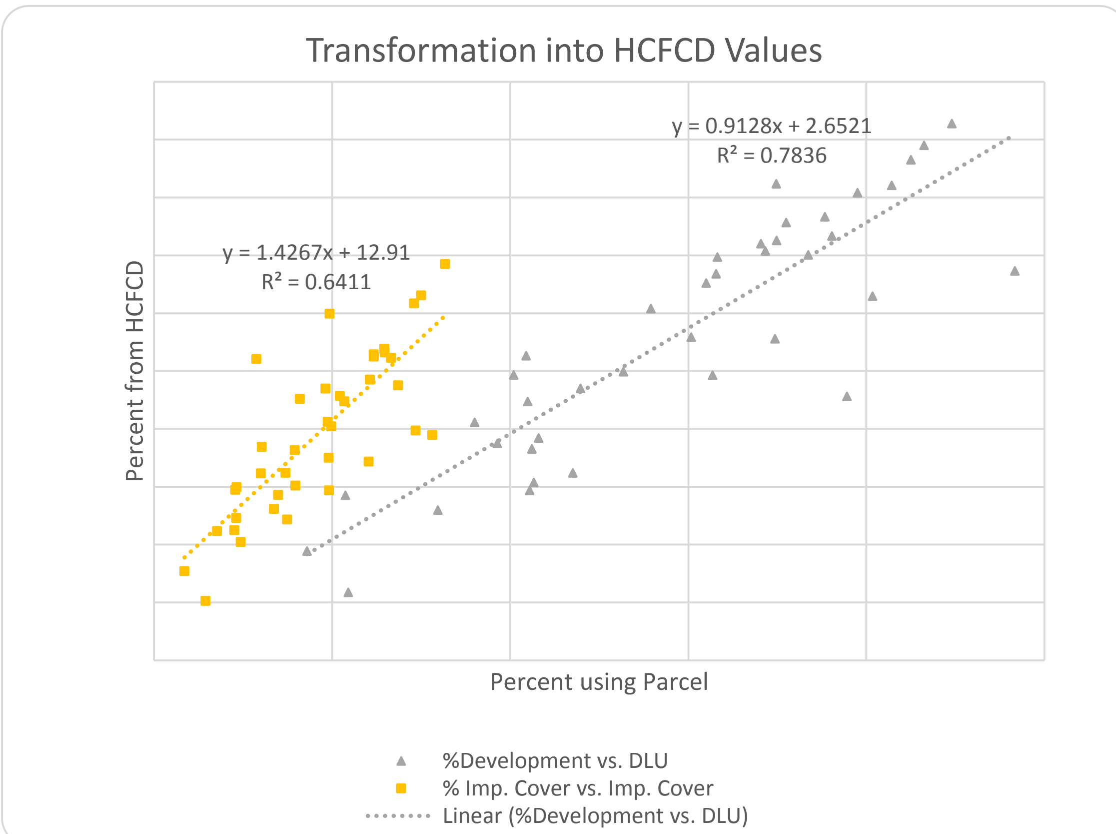



Figure 18- Comparison of percentage of development and impervious cover in HCFCD HEC-HMS model and methods used in this study.

This is most likely linked to the lack of information about commercial and industrial parking lots, driveways, and sidewalks in both of the appraisal districts tax rolls. Thus, many parking lots were left unaccounted for in the industrial and commercial buildings. Furthermore, percentages of imperviousness in the model were not assigned on a parcel by parcel basis but rather based on photography and land use category using different impervious cover percentages. Additionally, imperviousness of water bodies were counted as 100% in the model whereas imperviousness of water bodies using parcel data was counted as 0% (District 2009). These differences in the methodology are believed to account for the lower values of impervious cover that were derived from parcel data by this research.

Since the models were calibrated and validated using a specific methodology, the development and impervious cover values obtained from the marcel maps was not adequate. To address this difference, an adjustment factor using the ratio of model values to development map values for 2002 was applied to development and impervious cover values in 1980, 1990, and 2000. This adjustment factor assumed that changes in development were related spatially and that the adjustment factor for one subbasin would be unique and not change through the twenty-year period of 1980 to 2000. After the adjustment factor was applied, the watershed experienced an increase in development of 9.4% and an increase in impervious cover of 5.7% from 1980 to 2000.This increase was calculated using the adjusted values for development and impervious cover from 2000 and 1980 per subbasin and determining the corresponding amount of area for each one. The developed areas were summed among all subbasins for both scenarios and a percent difference was calculated using the changes in developed or impervious surface area and the watershed area The adjusted values for development and impervious cover were used to calculate new values for the time of concentration, $T_c$, and storage coefficient, S, used in the Clark Unit hydrograph following the procedure from Figure 16. After the changes in subbasin characteristics were finished, the model was run and the flows at different locations in the model were obtained. This procedure was repeated for each of the three stages of development. By comparing the values of discharge for the three stages, an increase of approximately 5% (4.8%) was observed from the development stage in 1980 to that of 2000 at the outlet of the Sims Bayou watershed. This amounted to an additional 1962 $ft^3/s$ for the same rainfall amount and distribution.

### *4.8 Hydraulic Modeling with HEC-RAS*

To assess the significance of a 5% change in flow for the watershed, the flows at all locations of the model were obtained for the three development stages. These flows were associated with certain locations in the watershed along Sims Bayou. The model included location descriptions at model junctions and reaches to match with cross-section stations. The hydraulic model for Sims Bayou consisted of 13 separate models, one for each major stream in the watershed. Each stream model included several cross-sections whose geometry had already been determined by land surveys or aerial photography. A total of 931 cross-sections were used in the stream models for the Sims Bayou watershed as seen in Figure 19. Flows obtained from HEC-HMS do not contain any flows upstream of subbasin outlets. However, the HEC-RAS models included cross-sections located along the various streams, but upstream of the subbasin outlet. Since flows accumulate and increase as water flows downstream, each cross-section will experience a different discharge. To account for this variable flow, the model had flow change locations. The flows at these stations were distributed based on percent of watershed area that would drain to that cross-section (HCFCD 2009). Using the original models, flows at each subbasin from HEC-HMS and flows at flow change locations from HEC-RAS were compared to determine a drainage area weight factor for each cross-section where a flow change occurred. Using this weighted factor, the flows for 1980, 1990, and 2000 were distributed to the cross-sections upstream of the outlet point for all the streams in the model. An example assignment of flows to flow change location using the weighted area factors can be seen in Table 5 below.

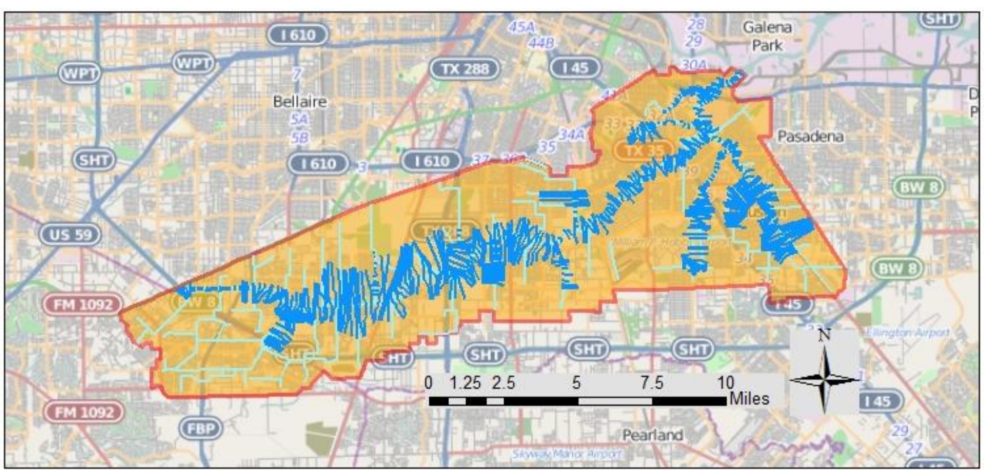



Figure 19- Stream network from NHD and cross-sections in HEC-RAS models from HCFCD

Table 5-Flow change locations and assignment of new flows

| River | Reach | RS | 1PCT_100yr | | Q/Qp | 1980 | 1990 | 2000 |
|---|---|---|---|---|---|---|---|---|
| C118-00-00 | C118-00-00_0009 | 6143.9 | 1988 | Qp from | 0.652231 | 1955 | 1972 | 1981 |
| C118-00-00 | C118-00-00_0009 | 4109.2 | 2422 | HMS= | 0.794619 | 2382 | 2402 | 2414 |
| C118-00-00 | C118-00-00_0009 | 863.9 | 3048 | 3047.8 | 1 | 2998 | 3023 | 3038 |
| | | | | | | | | |
| | | | | | Qp= | 2998 | 3023 | 3038 |

After new flows for each flow change location were determined, the HEC-RAS model was run with all three profiles evaluating the profiles as subcritical flow and using normal depth as the downstream boundary condition. Slopes used for normal depth calculation were provided with the model. After running the model, results were checked for accuracy. Velocities, flow width, and flow depth were compared among the 1980, 1990, 2000, and original 2002 profiles to check that values at the different cross-sections had similar characteristics. The results were then exported to GIS for floodplain mapping. Although HEC-RAS has a mapping utility for floodplain mapping using topography in a floating point grid format, the size and resolution of the DEM made it inconvenient to use. Instead, the GeoRAS toolset was used to import the HEC-RAS export file and DEM for the areas of interest. For easier processing, the DEM projected in Texas South Central State Plane System in feet was clipped to tiles that covered the extent of each reach subbasin only. Therefore, a different tile containing elevations only for the area of that reach's subbasin was used in GeoRAS. After import, the water surface TIN was generated and the floodplain was mapped for 1980, 1990, and 2000 by reach for a total of 13 floodplains for each of the development stages. All the stream floodplains were merged by development stage and their floodplain areas were compared. The change in floodplain area in the watershed amounted to approximately a

15% increase in flooded area in 2000 in comparison with the 1980 flooded area. Details of the changes in floodplain area can be seen in Figure 20 below.

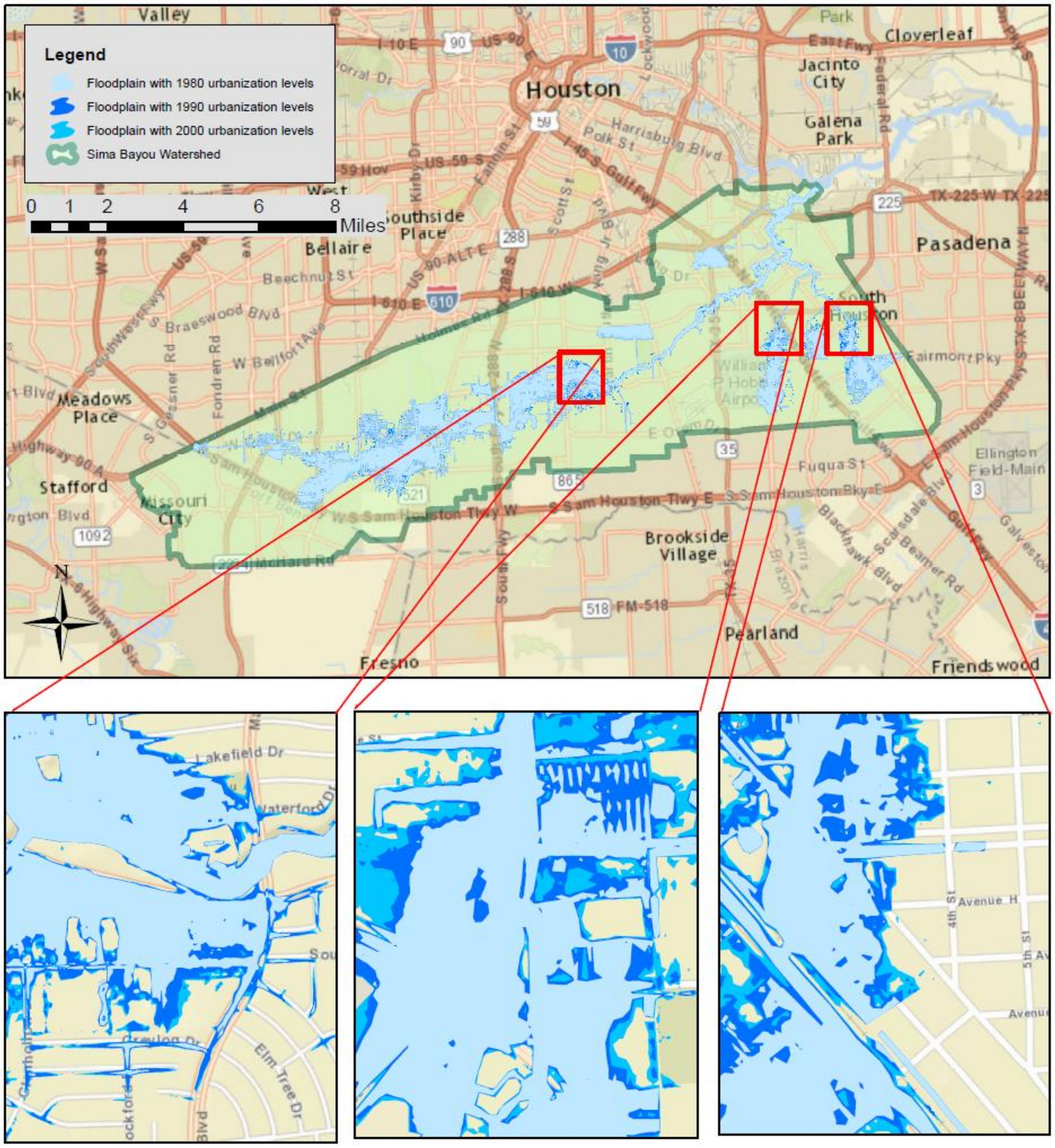



Figure 20- Regulatory floodplain in the Sims Bayou watershed modeled using development stages in 1980, 1990, and 2000.

# 5. DISCUSSION

Increasing runoff in a watershed alters its hydrologic behavior causing negative ecological and geomorphic effects on the receiving streams while increasing the flood risk for residents within and in close proximity to the floodplains. The Sims Bayou watershed has developed significantly over the last 50 years, and increasing impervious cover seems to be adding to flooding risk. After delineating the watersheds of interest along Sims Bayou, and using yearly development maps created with GIS from appraisal district parcel data, both peak flow and annual runoff discharges were analyzed through time in gages 08075400 and 08075500. For both gages, there was a positive increasing trend between peak flows and time, and between ratio of annual runoff/rainfall and impervious cover.

The statistical analysis using the Kruskal-Wallis non-parametric test for difference of means for both peak flows and average daily flows per decade revealed that whereas peak flows per decade in both gages were not significantly different using a level of 0.05 ($P = 0.272$, and $P = 0.058$), average daily flows per decade in both gages were significantly different ($P = <0.0001$, $P = <0.0001$). The lack of significance for peak flows per decade are not definitive, however, since the p-value for the flows in gage 08075500 was 0.058, just above significance. This is important given the use of a non-parametric test with lower strength than a parametric ANOVA would provide. Because of the low margin of difference between the p-value and significance level, the lack of significance for this gage is questionable. Such was not the case for gage 08075400 with a p-value much higher than the significance level. The difference may be attributed to the location of the watershed for gage 08075400 which lies at the uppermost part of the Sims Bayou watershed. Its location renders the watershed to slower development due to its distance from the center of the City of Houston. Thus, development levels and/or configuration in the watershed may not have achieved the threshold necessary to observe changes in hydrologic behavior.

The distribution of daily flows also seemed to change. The 75$^{th}$ percentile daily flow per decade for both gages increased consistently per decade. This shows that the stream is being affected by growing runoff on a day-to-day basis, not only during large flooding events. Although the 25$^{th}$ percentile daily flows for both gages generally had the same trend, flows for gage 08075400 showed a decrease in 25$^{th}$ percentile flows for the decade of 2000. This was unexpected, but may be explained by the drought of 2000 which followed a couple of already dry years. The drought conditions coupled with the location of the gage in the upper part of the watershed may explain the lower flows in the 2000s associated with lower rainfall and lower baseflow conditions. Conditions for gage 08075500 for the decade of 2000 were not available for analysis due to the large amount of missing data, but it is expected that those flows too would have displayed a similar decrease in the 25$^{th}$ percentile flows although the effects may have been buffered by the larger drainage area which could contribute more water.

Development levels in the Sims Bayou watershed per subbasin in 1980, 1990, and 2000 were used to modify the parameters for the existing HEC-HMS hydrologic model for the watershed. Using HEC-HMS and the development maps created, flows observed after development changes to year 2000 levels in the model parameters amounted to approximately 5% higher flows than flows obtained using 1980 development levels. This 5% increase in flow was a direct effect of increasing development in the watershed by 9.4% with an impervious cover increase of 5.7%. These results imply that the changes in flow at the outlet resulting from changes in impervious cover are almost on a 1:1 ratio. These results do not take into account channel improvements and other stormwater management infrastructure such as regional detention facilities that may have been built or changed throughout the 20-year period of analysis and which may have offset increases in discharge. However, this should be a fair estimate given that values for channel improvements, conveyance, and area served by on-site detention storage remained unchanged in the models. The values for improvement characteristics used in the model reflected conditions in 2002 which are assumed to have greater amount of improvements than would have actually been there in 1980 and 1990. The flows resulting from model runs for 1980, 1990, and 2000 were distributed along the stream cross-sections in the HEC-RAS hydraulic model and the regulatory floodplain was mapped for these three stages of development. The changes in floodplain area of the watershed from 1980 to 2000 amounted to a 15% increase from 1980. The increase in floodplain area, however, was not uniform throughout the watershed. Although the elevations of the Houston area are generally flat, there were certain regions within the watershed that were affected more than others. The largest changes were observed in the middle of the watershed and along the two major tributaries. These are also the most likely regions to be affected by higher runoff in the streams from the smaller storms.

## 6. STORMWATER MANAGEMENT BEST PRACTICES

Last year, over 19 miles of stream along Sims Bayou were improved to keep the 100-year flood within stream banks, but with the rising development in the area there are a number of low-impact designs that may provide several additional benefits to the conventional stormwater management techniques. Higher runoff is not only linked to higher flooding risk, but also to reduced groundwater recharge, widening and straightening of stream channels, and higher levels of pollution and nutrients in waterways. One possible alternative to impervious surfaces like asphalt are pervious pavement that restore the infiltration capacity of the watershed by permitting precipitation to infiltrate back to the soil and both retain and treat water while recharging groundwater. Pervious pavement provides the durability needed for commercial parking lots and eliminate virtually all runoff for low-intensity storms (Brattebo and Booth 2003). Vegetated roofs may also provide a high durability alternative with a reduction in runoff amount as well attenuation and delay of peak flows for a given precipitation event. However, as precipitation depth increases, the retention capabilities decrease from 88% to 48% and peak flow delays can shrink with wet antecedent moisture conditions (Carter and Rasmussen 2006). Yet, for industrial and commercial areas with large building size, vegetated roofs can reduce the amount of runoff for more common, low-intensity storms.

Both of these alternatives have best performance in soils with high permeability and low rainfall. For Houston, its clayey soils and history of tropical storms and hurricanes may diminish the performance of these measures. Although they will still provide infiltration and reduction in runoff, the benefit may not be enough to outweigh the costs to developers for implementing them. Thus, low-impact development alone will not be enough for a city already heavily urbanized. For Houston, a combination of low-impact development and a change in policy is needed. Measures as simple as reducing the width of subdivision roads from 32 ft. to 20 ft. can reduce the amount of impervious cover by 37.5% per linear mile. For commercial and industrial zones, parking lots are the best place for reduction of impervious cover since there is usually an oversupply of spaces. A reduction in the minimum parking spaces required for commercial and industrial development would greatly reduce impervious cover since developers already usually include up to 51% more parking spaces than required. Parking lots usually also incorporate raised landscape beds, but making these beds lie below the pavement grade can provide infiltration and runoff treatment(Arnold 1996). By turning raised plant beds into below-grade infiltration zones in other applications like cul-de sacs, the amount of runoff produced by impervious cover that reaches the stream can be reduced.

The City of Houston has a long history of flooding issues that are well-known to its residents. In its attempt to update and upgrade the dated drainage infrastructure in place, the city of Houston has finally taken a step to limit impervious cover. In April of 2014 an impervious coverage based impact fee for new developments became effective. This fee is meant to distribute the costs of expanding drainage infrastructure for new developments based on the amount of impervious coverage units developed (1000 $ft.^2$ of impervious surface = 1 unit). The fee ranges from $0 to $17 depending on the service area where the development occurs. These service areas align with the HCFCD's delineations for the TSARP watershed boundaries. Developers building in Sims or Vince Bayou watersheds face the highest fees per unit (Rebuild Houston 2015). Making the impact fee for Sims Bayou watershed the highest should detract developers from building and motivate them to integrate low-impact design alternatives when working in the Sims Bayou watershed.

# 7. CONCLUSION

Increasing impervious cover in a watershed has long been linked to increasing flows in streams which can cause changes in geomorphology and ecological quality of the stream. For the Sims Bayou watershed in Houston, Texas, the increase in development in the last 50 years has caused an increasing trend in peak flows and annual runoff observed in the two gages with longest period of record for the watershed. Development maps created from appraisal district parcel data were used to analyze the growing trend of flows with the rise in development in the watersheds. Although the peak flows were not significantly different among the decades of analysis, the average daily flows observed at both gages were significantly different with higher daily flows occurring on a more frequent basis every decade. The existing HEC-HMS model was modified to reflect development levels from 1980 to 2000. The resulting flows at the outlet of the watershed for development levels of 2000 were 5% higher than those of 1980. This 5% increase in flow represented a 12.7% change in the floodplain area within Sunnyside and a 4.7% change in floodplain area within Manchester. Although the change in flow seems small, this analysis only accounted for 20 years of development change, and for many residents of Sims Bayou who have lived in their homes for decades, the changes are more apparent.

Even though the HCFCD and USACE have partnered to improve the channels along Sims Bayou to reduce flood risk, increasing urbanization may diminish the success of these measures in the near future. Stormwater management best practices can help alleviate some of the flooding risk by providing more infiltration and reducing runoff amounts and storm peak flows. However, with the clayey soils and the high amounts of precipitation in Houston, the expected benefits may not be enough to outweigh the costs. Thus, for Houston, both better development practices and policy need to be implemented. Hopefully, with the use of the impact fee that became effective in 2014, development in the Sims Bayou watershed will slow down and integrate more stormwater management best practices into current and future development.

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